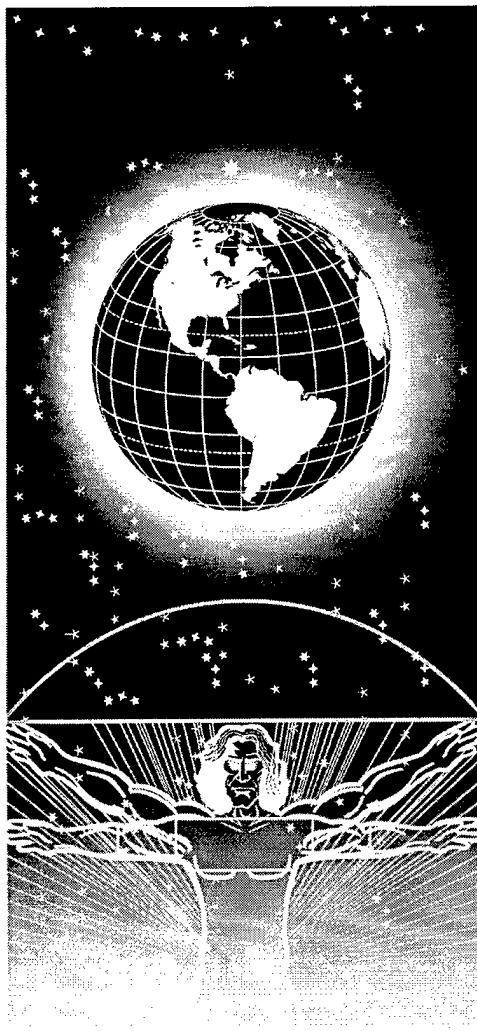


AL/EQ-TR-1997-0024



UNITED STATES AIR FORCE
ARMSTRONG LABORATORY

Six-Phase Soil Heating of the Saturated
Zone, Dover Air Force Base, Delaware

T. M. Bergsman and L. M. Peurrung

BATTELLE PACIFIC NORTHWEST LABORATORY
Battelle Boulevard
P. O. Box 999
Richland, WA, 99352

November 1997

19971215 012

DTIC QUALITY INSPECTED 3

Approved for public release; distribution is unlimited.

Environnics Directorate
Environmental Risk
Management Division
139 Barnes Drive
Tyndall Air Force Base FL
32403-5323

NOTICES

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any employees, nor any of their contractors, subcontractors, or their employees, make any warranty, expressed or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any privately owned rights. Reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency, contractor, or subcontractor thereof. The views and opinions of the authors expressed herein do not necessarily state or reflect those of the United States Government or any agency, contractor, or subcontractor thereof.

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely Government-related procurement, the United States Government incurs no responsibility or any obligation whatsoever. The fact that the Government may have formulated or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication, or otherwise in any manner construed, as licensing the holder or any other person or corporation; or as conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

This technical report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS) where it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

FOR THE COMMANDER:



PAUL B. DEVANE, Maj, USAF, BSC
Project Manager



ALLAN M. WEINER, Lt Col, USAF
Chief, Environmental Risk Management
Division

DRAFT SF 298

1. Report Date (dd-mm-yy) November 1997	2. Report Type Final	3. Dates covered (from... to) September 1996 to November 1997		
4. Title & subtitle Six-Phase Soil Heating of the Saturated Zone Dover Air Force Base, Delaware		5a. Contract or Grant # F08637-95-D-6004		
		5b. Program Element # 62202F		
6. Author(s) T.M. Bergsman and L.M. Peururing		5c. Project # 1900		
		5d. Task #		
		5e. Work Unit # W501		
7. Performing Organization Name & Address Battelle Pacific Northwest Laboratories Battelle Boulevard P.O. Box 999 Richland, WA 99352		8. Performing Organization Report #		
9. Sponsoring/Monitoring Agency Name & Address Armstrong Laboratory Environics Directorate Environmental Risk Management Division 139 Barnes Drive, Suite 2 Tyndall Air Force Base, FL 32403-5323		10. Monitor Acronym USAF		
		11. Monitor Report # AL/EQ-TR-1997-0024		
12. Distribution/Availability Statement Approved for public release. Distribution unlimited.				
13. Supplementary Notes				
14. Abstract As part of Armstrong Laboratory's efforts to identify technologies to treat Dense Non-aqueous-Phase Liquids (DNAPL), a field test of Six-Phase Soil Heating (SPSH) was performed at the Groundwater Remediation Field Laboratory (GRFL) at Dover Air Force Base. The goal of the test was to determine the effectiveness of SPSH for heating the aquifer to temperatures sufficient to remove target DNAPL contaminants. This field test was conducted in an uncontaminated aquifer using tracer compounds to mimic DNAPLs commonly found at Air Force sites. Six-Phase Soil Heating uses electrical resistance to raise the temperature of the soil and groundwater to boiling. A single, six-electrode array was installed into the aquifer (approximately 34 feet below ground surface) at the GRFL site. Temperatures in the saturated zone rose to boiling over 12 to 17 days. Heating and boiling of the aquifer continued for another 13 days. Tracer sampling results showed no significant migration of the tracers in the groundwater, some migration of tracers in the unsaturated zone, full recovery of the perfluoromethylcyclohexane (PMCH) (continued on next page)				
15. Subject Terms Six-Phase Soil Heating, resistive heating				
Security Classification of			19. Limitation of Abstract	
16. Report Unclassified	17. Abstract Unclassified	18. This Page Unclassified	Unlimited	20. # of Pages 57
			21. Responsible Person (Name and Telephone #) Maj Paul B. Devane (850) 283-6288	

14. Abstract Cont.

in the extracted offgas, and 35 percent recovery of the perfluorotrimethylcyclohexane (PTMCH). Most of the tracer removal occurred in 21 days.

PREFACE

This report was prepared by the Pacific Northwest National Laboratory, Battelle Boulevard, Richland, Washington 99352, under Task 5A of Contract No. F08637-95-D-6004, for the Armstrong Laboratory Environics Directorate (AL/EQ), 139 Barnes Drive, Suite 2 Tyndall Air Force Base, Florida 32403-5323.

The Pacific Northwest National Laboratory is operated for the U.S. Department of Energy by Battelle under Contract DE-AC06-76RLO 1830.

The authors wish to acknowledge the on-site support of the staff at the Groundwater Remediation Field Laboratory, operated by Applied Research Associates, Inc.

This final report describes the demonstration of the Six-Phase Soil Heating (SPSH) technology for DNAPL removal. The report includes performance data, a study of tracer migration control and recovery, an analysis of energy requirements, a discussion of technology issues, and an economic analysis.

The demonstration was performed between September 1996 and March 1997 at Dover Air Force Base, Delaware. The AL/EQ project officer was Major Paul DeVane.

EXECUTIVE SUMMARY

A. BACKGROUND

In August 1995, Armstrong Laboratory's Environics Directorate selected Six-Phase Soil Heating (SPSH) as part of their program to identify technologies for treating Dense Non-aqueous-Phase Liquids (DNAPLs) in the saturated zone. An expert panel reviewed various technologies, and SPSH was identified as a promising technology for further evaluation. Six-Phase Soil Heating uses electrical resistive heating to raise the temperature of soil and groundwater to boiling, creating an insitu source of steam to strip contaminants. A field test was performed at the Groundwater Remediation Field Laboratory (GRFL) at Dover Air Force Base, Delaware, to determine the effectiveness of SPSH for heating the aquifer sufficiently to remove target DNAPL contaminants. This field test was conducted in an uncontaminated aquifer using tracer compounds to mimic DNAPLs commonly found at Air Force sites.

B. DESCRIPTION OF DEMONSTRATION

A single, six-electrode array was installed into the aquifer at the GRFL site. The stratigraphy at the site consisted of sand, gravel, thin clay layers and silt to a depth of 33.5 to 34 feet below ground surface (bgs) and an underlayer of dense clay containing thin laminations of silt and fine sand. The water table was located at approximately 25 feet bgs and extended to the clay layer, forming an aquifer with a total thickness of about 5 to 7 feet in the upper high permeability region. Electrodes were installed to a depth of 35 feet bgs, and the active heated region extended from 20 feet bgs to 35 feet bgs. This design allowed heating of not only the aquifer but also approximately 5 feet of the vadose zone above the aquifer to assist in steam collection. The diameter of the electrode array was 30 feet, creating a heated zone roughly 42 feet in diameter and 15 feet thick for a total heated soil volume of about 800 yd³ (600 m³). Nonhazardous organic tracers mimicking DNAPLs were added to the heated region to study their migration and to test the effectiveness of the vapor extraction system in removing DNAPL mobilized by SPSH. The vapor extraction system used for this demonstration was designed as part of the electrode array to collect both steam and mobilized contaminants from each electrode and from a central vent.

The above-surface equipment included a transformer to convert standard three-phase line power into six phases, a collection header, a vacuum blower, a condenser and knockout box, and granulated activated carbon drums to treat both the off gas and condensate. A water addition system was also installed in case additional moisture was needed to maintain conduction at the electrodes; however, this system was never needed.

C. RESULTS

Power was applied to the array beginning on February 7, 1997. Over 12-17 days, temperatures in the saturated zone rose to boiling. Heating and boiling of the aquifer continued for another 13 days while sampling for the tracers proceeded. The total duration of the heating operation was 30 days, during which 50,000 gallons of condensate were removed from the site, an amount roughly equal to all the subsurface moisture initially in that region. The energy used over 30 days was 200,000 kW-hrs. Most of the tracer was removed over 21 days. The energy used up to that time was 136,000 kW-hrs, and the condensate removed was 29,000 gallons.

Tracer sampling results showed no significant migration of tracers in the groundwater, some migration of tracers in the unsaturated zone, full recovery of the perfluoromethylcyclohexane (PMCH) in the extracted off gas, and 35% recovery of the perfluorotrimethylcyclohexane (PTMCH). The fate of the remaining PTMCH is uncertain. Its appearance in the off gas may have been missed during an outage of the analytical system. Moreover, soil vapor and off-gas analyses at the end of the operation were consistent with the view that a negligible amount of the PTMCH remained in the subsurface.

D. CONCLUSIONS

Six-Phase Soil Heating was successful in heating the aquifer to levels sufficient to remove target DNAPL contaminants. Temperatures within the heated region exceeded the target heating temperatures, and boiling occurred throughout the aquifer.

A significant portion of the injected tracers was removed during treatment, indicating that SPSH has the potential to treat DNAPL. The apparent lower recovery of PTMCH may be due to loss of data between sampling events.

Soil vapor samples suggest that the tracer compounds did migrate outward through the vadose zone when steam was first generated, indicating incomplete control of vapor by the off-gas collection system. However, the high recovery of PMCH (the tracer placed at the edge of heating) indicates that an increase in the vacuum applied to the soil during the operation enabled an overall high capture efficiency for the system.

Groundwater samples showed no measurable tracer at any time during the demonstration.

Energy requirements for SPSH treatment of an aquifer were roughly as predicted. At 20 percent of the total cost, energy costs are an important part, but not a majority of the overall treatment cost. For the 30-day test, 200,000 kW-hrs were used and 50,000 gallons of condensate were collected. Most of the tracer was removed during the first 21 days of heating. During that period, 136,000 kW-hrs were used and 29,000 gallons of condensate were collected. At \$0.07 per kW-hr, this represents an energy cost of \$9,500 or approximately \$16 per cubic meter heated.

E. RECOMMENDATIONS

Six-Phase Soil Heating is applicable for full-scale deployment at a DNAPL site. The GRFL demonstration was successful at showing that the technology can be used to heat a flowing aquifer to temperatures sufficient to remove targeted DNAPL compounds. The technology has also been deployed, full scale, at a saturated, tight-soil DNAPL site in Chicago where it was successful in removing over 12,000 pounds of perchloroethylene contaminant in six months. The success of the GRFL demonstration and the Chicago deployment support moving forward with a full-scale demonstration or deployment of this technology.

The six-phase transformer, vacuum blower, and condenser operated well; however, the condensate collection system had numerous problems. The condensate collection system should be modified for future demonstrations. This will also allow continuous operation of the vapor collection system at higher vacuums, improving vapor collection.

TABLE OF CONTENTS

Section	Title	Page
I	INTRODUCTION.....	1
	A. OBJECTIVES	1
	B. BACKGROUND	2
	C. SCOPE.....	3
II	SITE DESCRIPTION	5
	A. LOCATION AND SETTING	5
	B. GEOLOGY AND HYDROGEOLOGY	5
III	DEMONSTRATION DESCRIPTION	7
	A. TECHNOLOGY PRINCIPLES	7
	B. TREATMENT SYSTEM INSTALLATION	8
	1. Subsurface Monitoring System Installation	8
	2. Electrode and Vent Well System Installation	11
	3. Above Ground Equipment Installation: Venting System.....	14
	4. Above Ground Equipment Installation: Electrical System and Instrumentation Connection.....	14
	C. TREATMENT SYSTEM OPERATION.....	18
	D. SAMPLING STRATEGY	19
	1. Approach.....	19
	2. Sampling and Analytical Methodology.....	20
	3. Data Needs	20
	4. Operation.....	21
	E. QA RESULTS	21
IV	TECHNOLOGY PERFORMANCE EVALUATION	25
	A. PERFORMANCE DATA.....	25
	1. Soil and Aquifer Heating Measurement.....	25
	2. Tracer Migration and Recovery	28

3.	Soil Vapor	33
4.	Groundwater	36
C.	REMEDIATION EFFECTIVENESS	36
D.	SYSTEM PERFORMANCE: ENERGY USAGE AND STEAM GENERATION.....	36
V	OTHER TECHNOLOGY ISSUES.....	37
A.	ENVIRONMENTAL REGULATION REQUIREMENTS.....	37
B.	PERSONNEL AND HEALTH AND SAFETY ISSUES.....	37
C.	COMMUNITY ACCEPTANCE	37
VI	ECONOMIC ANALYSIS.....	39
A.	SITE SCENARIO	39
B.	COST ANALYSIS.....	39
VII	CONCLUSIONS.....	43
VIII	RECOMMENDATIONS	45
	REFERENCES	47
	APPENDIX A	49
	NOTICE	57

LIST OF FIGURES

Figure		Page
1	Six-Phase Soil Heating Schematic.....	4
2	Schematic Layout of Six-Phase Soil Heating Array and Injection Monitoring Wells.....	9
3	Layout of As-Built Monitoring Network	10
4	Typical Electrode Installation As Built.....	12
5	Vent Well Installation As Built.....	13
6	Groundwater and Vapor Sampling Wells	15
7	Soil Vapor Extraction System.....	16
8	Six-Phase Soil Heating Site Looking North	16
9	Six-Phase Transformer and Electrodes.....	17
10	Vapor Extraction Header	16
11	Readings From Temperature Well T1 Immediately Up Gradient from Heated Zone	25
12	Readings from Temperature Well T2 within the Heated Zone.....	26
13	Readings from Temperature Well T3 within the Heated Zone.....	26
14	Readings from Temperature Well T4 Immediately Down Gradient from the Heated Zone	27
15	Readings from Temperature Well T5 Down Gradient from the Heated Zone	27
16	Saturated Zone Temperatures	29
17	Vacuum at P1 and P2 compared to Vadose Zone Temperatures on Well 4.....	29

18	Tracer Concentrations in ppb,v in the Off Gas during Six-Phase Soil Heating Operations	30
19	Tracer Collection Rate during Six-Phase Soil Heating Operations	31
20	Cumulative Amount of Tracers Collected during Six-Phase Soil Heating Operations	31
21	Vertical Cross-Section of Expected Subsurface Flows Induced by Soil Venting and Relative positions of Tracers and Soil Vapor Sampling Wells.....	34
22	PMCH Concentrations in Soil Vapor from Four Extraction Wells.....	35
23	PTMCH Concentrations in Soil Vapor from Four Extraction Wells.....	35

LIST OF TABLES

Table		Page
1	Physical Properties of TCE, PCE and Surrogate Tracer Compounds.....	2
2	Tracer Injection Amounts and Locations	21
3	Apparent Tracer Concentration in Field and Equipment Blanks	23
4	Precision of Samples Taken during SPSH Demonstration as Measured by Field Duplicates	24
5	Estimated Amount and Percentage of Tracer Collected during Operation.....	30
6	Cost Estimate for One Acre DNAPL Site.....	41

LIST OF ACRONYMS

AFB	Air Force Base
bgs	below ground surface
CERCLA	Comprehensive Environmental Response Compensation and Liability Act
CPT	cone penetrometer
CPVC	chlorinated polyvinyl chloride
DAS	data acquisition system
DNAPL	Dense Non-aqueous-Phase Liquid
EPA	U.S. Environmental Protection Agency
GAC	granulated activated carbon
GC	gas chromatograph
GRFL	Groundwater Remediation Field Laboratory
NAPL	Non-aqueous-Phase Liquid
PCE	perchloroethylene
PMCH	perfluoromethylcyclohexane
ppbv	parts per billion, volumetric
PTMCH	perfluorotrimethylcyclohexane
QA	Quality Assurance
QAPP	Quality Assurance Project Plan
RPD	relative percent deviation
SCFM	standard cubic feet per minute

SPSH Six-Phase Soil Heating

SVE Soil Vapor Extraction

TCE trichloroethylene

SECTION I

INTRODUCTION

A. OBJECTIVES

The objectives for this test were developed to assess SPSH performance in removing DNAPL contamination. The first primary objective was to determine if SPSH was effective at heating a flowing aquifer to temperatures necessary to remove DNAPL contaminants. Common DNAPL contaminants at Department of Defense sites requiring environmental restoration are trichloroethylene (TCE) and perchloroethylene (PCE). Six-Phase Soil Heating aims to enhance the gas-phase transport in two ways:

- If the contaminant of concern is a pure phase (NAPL) and the temperature is sufficient to create boiling (i.e., the combined vapor pressures of water and the contaminant exceed the total pressure in the treatment zone), the contaminant will form gas bubbles and travel through the surrounding water to be released into the vadose zone. For TCE and PCE under 10 feet of water, these temperataures are 80°C and 95°C respectively. Boiling occurs at less than the boiling point of the pure phase contaminant because the vapor pressure of the water and the contaminant combine. The resulting gas-phase concentrations are also a combination of water and contaminant depending on their respective vapor pressures at that temperature.
- If the temperature reaches the boiling point of water, steam bubbles will remove the contaminant by "steam stripping". The rate at which the contaminant is removed will depend on the steam-generation rate, the contact between the steam and the contaminant (dissolved or pure phase), soil sorption, and the equilibrium vapor-phase concentration of the contaminant, which varies with temperature and depends on whether or not the contaminants are dissolved, pure phase, or mixed with nonvolatile co-contaminants.

The second primary objective was to utilize tracer commppounds to access the potential for migration. The tracer compounds chosen for the initial demonstration, perfluoromethylcyclohexane (PMCH) and perfluorotrimethycyclohexane (PTMCH), mimic TCE and PCE in their physical properties but are nontoxic and nonhazardous. Table 1 shows the physical properties of TCE, PCE, and these two tracers.

TABLE 1. PHYSICAL PROPERTIES OF TCE, PCE, AND SURROGATE TRACER COMPOUNDS

Physical Properties:	TCE	PCE	PMCH	PTMCH
Boiling point, °C	87	121	76	127
Density, g/cm ³	1.46	1.62	1.788	1.888
Water solubility, ppm	1100	150	<1	<1

The specific objectives for the test were as follows:

1. Determine the effectiveness of SPSH in heating the aquifer to levels sufficient to remove target DNAPL contaminants
2. Quantify the total tracer mass removed by the process
3. Assess the performance of the SPSH treatment system
4. Determine the effectiveness of liquid migration control and recovery during the process
5. Determine the effectiveness of vapor migration control and recovery during the process
6. Determine the parameters governing the success of the process
7. Obtain data needed to determine the demonstration cost and the cost to scale up the technology
8. Adhere to the requirements for a CERCLA Treatability Study and obtain data suitable in quantity and quality to support selection of the technology for a final remedy.

Each of these objectives is described in detail in the project test plan. The tracer work specifically addresses objectives 2, 4, and 5, with the emphasis on assessing the control of mobilized contaminants rather than on a "mass balance" of the injected material. Such a mass balance is notoriously difficult when working with kilogram quantities of material.

B. BACKGROUND

Six-Phase Soil Heating is a resistive soil heating method that enhances the removal of volatile and semivolatile contaminants from soils (Bergsman et al. 1993a, 1993b). A schematic diagram of the process is shown in Figure 1. To implement the technology, electrodes are placed in the ground surrounding the contaminated region, and voltage is applied. Electrical current conducts through the soil moisture, heating the soil resistively. This heating volatilizes contaminants and water (producing steam), effectively steam-stripping contaminants in situ. The volatilized contaminants and steam are then removed by soil venting and are treated above ground by condensation and granulated activated carbon adsorption or other off-gas treatment methods. This process results in faster and more complete removal of target contaminants from soil compared to conventional methods, such as soil vapor extraction and pump and treat (U.S. Patents 5,347,070 and 5,545,803).

In the patented SPSH method, conventional single-phase transformers convert commercial line power to six-phase electricity. A separate electrical phase is connected to each of six electrodes arranged in a hexagon. Because of the unique phasing and spacing configuration, all six electrodes fire simultaneously. The consequent uniform heating pattern allows the use of fewer, more widely spaced electrodes than in other resistive heating systems.

Although SPSH has been successfully demonstrated for removing contaminants from the vadose zone (Gauglitz et al. 1994, Bergsman et al. 1994), its use to enhance remediation of groundwater is an innovative application. Because of the developmental nature of using SPSH in situ to remediate groundwater, a phased approach was taken to the demonstration of this application at the GRFL. This report discusses the first phase of operations, which demonstrates that SPSH can heat an uncontaminated aquifer. In addition, two tracer compounds with physical properties similar to a DNAPL contaminant were injected into the groundwater. Groundwater, soil vapor, and off-gas samples were collected and analyzed to demonstrate control and collection of contaminants. The second phase (future work) will apply SPSH to a contaminated aquifer.

C. SCOPE

The scope of the demonstration included:

- Installation of the equipment, including in-ground electrodes, vents, and wells, as well as above-ground systems to control power, treat off gas, and monitor the test site;
- Injection of the tracer compounds;
- Operation of the technology for a period of approximately 30 days while monitoring subsurface temperatures and tracer removal;
- Demobilization from the site;
- Disposal of generated wastes; and
- Data analysis and reporting.

This application analysis report discusses the results of the demonstration, the feasibility and cost-effectiveness of using SPSH to heat soil and generate steam in the saturated environment, and the ability to control and collect contaminants mobilized by SPSH using non-toxic tracers. Energy requirements, condensate generation rates, and subsurface temperature profiles were used to assess the technology's cost-effectiveness. Tracer migration and recovery were used to assess control of mobilized contaminants.

Six Phase Soil Heating

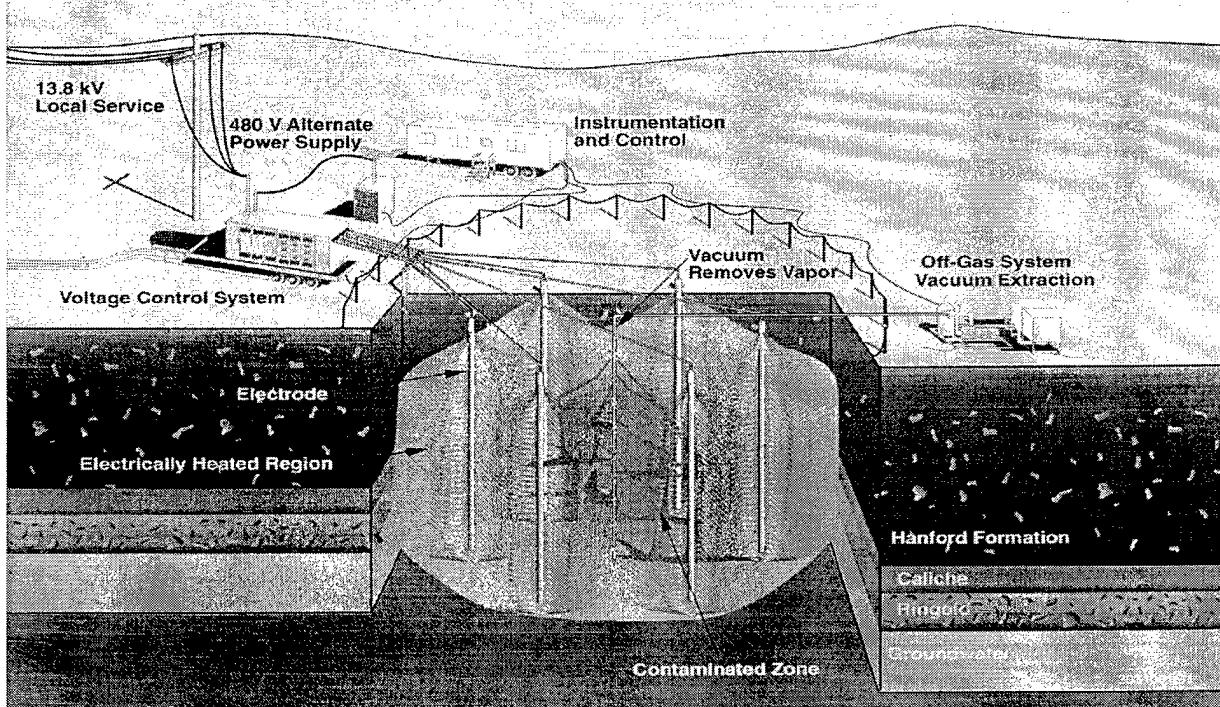


Figure 1. Six-Phase Soil Heating Schematic

SECTION II

SITE DESCRIPTION

A. LOCATION AND SETTING

Dover AFB is located 3 miles southeast of Dover, Delaware; 55 miles south of Wilmington, Delaware; and 92 miles east of Washington, DC.

Dover AFB maintains and supports the GRFL, located in a field at the northeast edge of the base. The GRFL is a test bed for field testing of technologies for the clean-up of soil and groundwater contaminated with fuels and solvents. The GRFL also maintains the capability to conduct contained releases of DNAPLs into a water table aquifer.

B. GEOLOGY AND HYDROGEOLOGY

Dover AFB is generally level, with little spatial variation. The surface elevation ranges from 10 to 35 feet above mean sea level.

The stratigraphy in this area consists of sand, gravel, thin clay layers and silt to a depth of 33.5 to 34 feet bgs and an underlayer of dense clay containing thin laminations of silt and fine sand. In the project test plan, the depth to the clay layer was originally estimated at 40 feet, leading to complications in installation of the subsurface equipment, as described below. In addition, the region immediately above the clay was found to be a 2-4-feet thick low-permeability layer of silty and clayey sandy gravel or sands and gravel with interbedded clay layers. The water table is located at approximately 25 feet bgs (as expected) and extends to the clay layer, forming the Columbia Aquifer with a total thickness of about 5-7 feet in the upper, high-permeability region. This aquifer is not used locally as a water source. Groundwater flow is approximately from southeast to northwest.

Pumping tests in the area gave hydraulic conductivities in the range of 3×10^{-3} cm/sec to 1×10^{-2} cm/sec and correlate with laboratory permeameter tests conducted on soil samples from the site. Pumping tests at the GRFL gave average hydraulic conductivities ranging from 2.8×10^{-3} to 1.2×10^{-2} cm/sec. Small scale vertical variations in hydraulic conductivity have been found to vary by as much as 2.5 orders of magnitude and may be related to changes in soil type.

The underlying clay of the Calvert Formation forms an aquitard with a thickness of 18 to 28 feet, averaging 22 feet. The vertical hydraulic conductivity of this unit has been estimated to be between 2.7×10^{-8} and 1×10^{-7} cm/sec.

(This page is blank.)

SECTION III

DEMONSTRATION DESCRIPTION

A. TECHNOLOGY PRINCIPLES

Six-Phase Soil Heating effectively removes volatile and semivolatile contaminants from soils (Bergsman et al. 1993a, 1993b). To implement the technology, electrodes are placed in the ground surrounding the contaminated region and voltage is applied. Electrical current conducts through the soil moisture and heats the soil resistively. This heating volatilizes contaminants and water (producing steam) in the soil, effectively steam stripping contaminants in situ. The volatilized contaminants and steam are then removed by soil venting and are treated above ground. This process results in accelerated and more complete removal of target contaminants from soil compared to conventional soil-vapor extraction (SVE) and does not require excavation.

The only additive required for SPSH treatment is water, which is normally added to the soil surrounding the electrodes during operations. This prevents the soil adjacent to the electrodes from drying out and becoming nonconductive. However, while a water addition system was installed for this demonstration, the moisture in the aquifer was sufficient to keep the electrodes conductive throughout operation. Therefore, no water was added to the subsurface during this demonstration.

The components required to implement SPSH are electrodes and vapor extraction vents installed subsurface, an off-gas collection and treatment system (including piping, a blower, a condenser, and a treatment unit), a transformer used to condition power for application to the soil, and a computer control/data acquisition system. (For a schematic of the system components, see Figure 1.) Continuous remote control of power with a personal computer throughout the test maintains optimum power delivery.

As the soil is heated, the volatile contaminants are collected and processed in an off-gas treatment unit. As the soil is cleaned, contaminant levels in the off gas decrease. When they reach acceptable levels (site and contaminant specific), the demonstration is terminated.

Six-Phase Soil Heating is implemented in arrays of six electrodes arranged in a hexagonal pattern. An array can be as large as 40 feet in diameter, effectively heating a 55-feet diameter region of soil. To treat large volumes of soil, several arrays can be operated simultaneously or the heated region can extend to a great depth (up to 200 feet below the surface). The maximum volume of soil treated is governed by the power-delivery capability of the SPSH transformer (5000 yd³ of soil can be treated with the existing 950 kVA transformer).

B. TREATMENT SYSTEM INSTALLATION

Installation of the field equipment began on September 23, 1996. Except as noted below, installation proceeded in accordance with the test plan. Subsurface installation activities included drilling, lithologic logging, subsurface monitoring system installation and well development, and the installation of the electrode/vent array.

1. Subsurface Monitoring System Installation

The subsurface monitoring system, shown in Figure 2 and in further detail in Figure 3, consisted of four types of systems: temperature monitoring wells (T1-T5), vadose zone wells (V1-V4), tracer injection wells (IA and IB), and groundwater monitoring wells (G1-G6). The as-installed locations of these subsurface installations were changed slightly by increasing the 1-foot spacings between some adjacent wells to 18 inches to avoid potential damage during installation.

Temperature wells were installed by cone penetrometer (CPT). Except for T2, thermocouples were spaced vertically at 5-foot intervals, starting from 12.5 feet bgs and extending into the aquitard to 42.5 feet bgs for a total of seven vertical locations. Because of coarse gravel present at 31 feet to 33 feet, T2 could not be driven past 32 feet bgs. The uppermost thermocouple on T2 is therefore only 2 feet bgs. Thermocouple bundles were taped together with duct tape every 2-3 feet. Because there was not enough space inside the 1.0-inch drive rod, they were not strapped to 0.5-inch CPVC pipe as originally planned. Instead, the lowermost thermocouple was attached to a special steel drive tip using epoxy.

Vadose zone monitoring wells were installed by CPT to a depth of about 20 feet bgs and completed with sand, bentonite, and cement grout in accordance with the test plan. Two of these wells, V2 and V3, were also used to monitor soil vacuum (P1 and P2, respectively).

Tracer injection wells were installed by CPT. The first installations (marked as "Old IA" and "Old IB" in Figure 3) were emplaced too deep into the clay aquitard because coring had not yet been completed to verify the depth to the aquitard. These wells were capped and were not used during the demonstration. Replacement wells new IA and new IB were installed next to the original wells to a depth of 29.8 and 30.8 feet bgs, respectively. The wells were then completed with about 6 feet of sand followed by bentonite and cement grout in accordance with the test plan.

Four of the six groundwater monitoring wells, G1, G2, G4, and G5 were installed by United Well Drilling (who also installed the temperature, vadose zone, and injection wells) in September, 1996 using CPT. The other two groundwater wells (G3 and G6) were installed in September by the Walton Corporation using a CME-55 hollow-stem auger due to driving difficulties at these two locations. The borings for these two wells had eight 1/4-inch diameters,

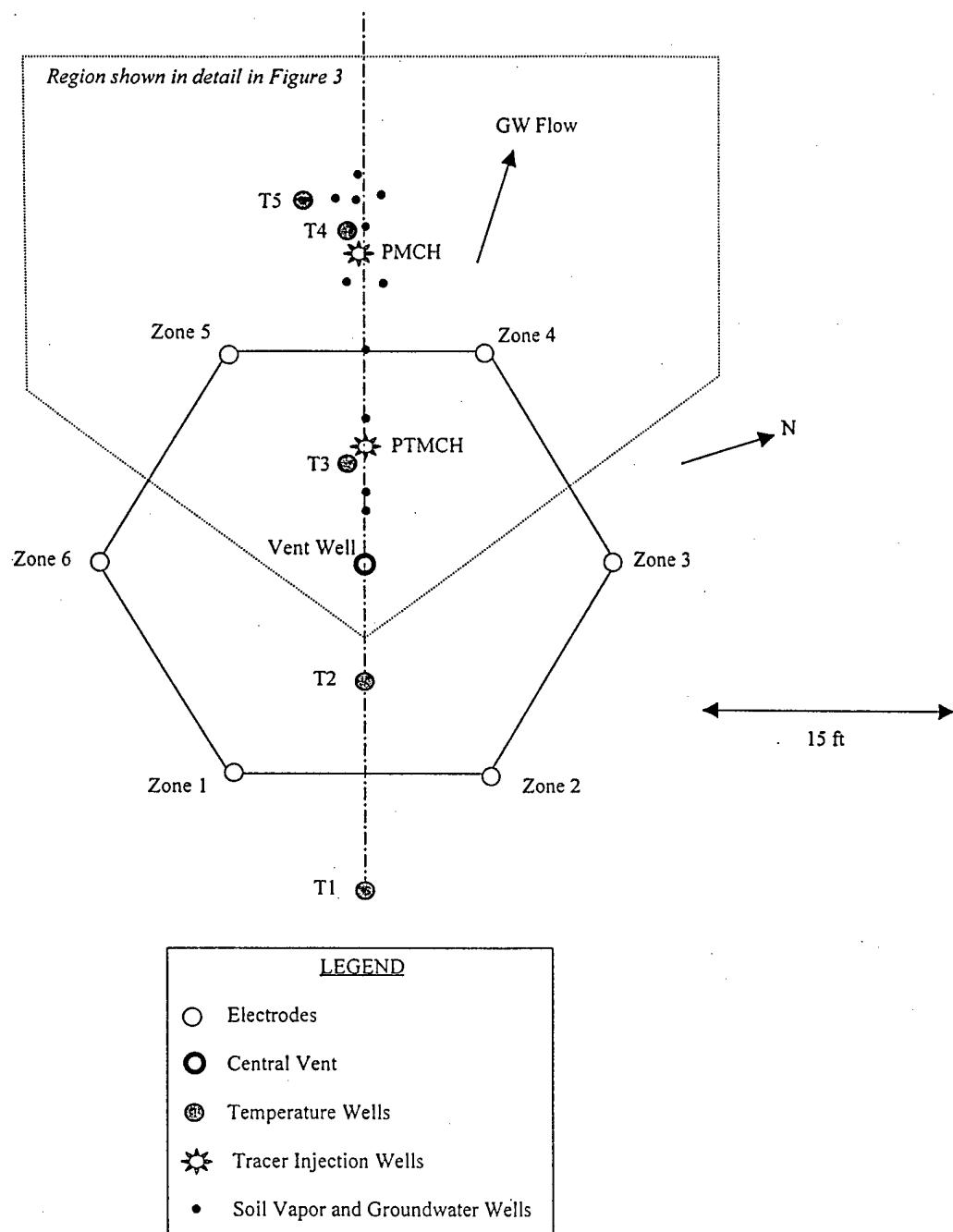


Figure 2. Schematic Layout of Six-Phase Soil Heating Array and Injection and Monitoring Wells.

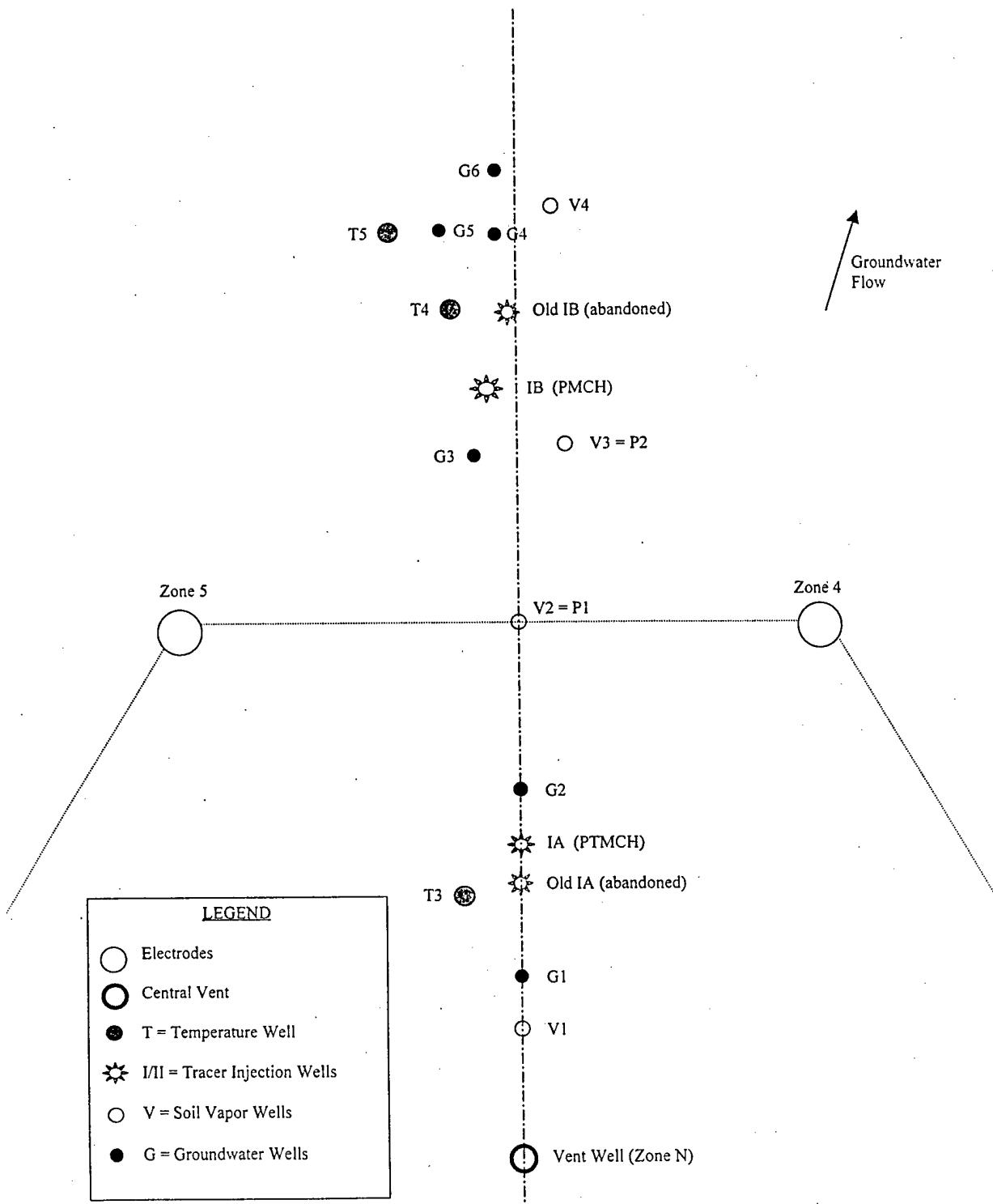


Figure 3. Layout of As-Built Monitoring Network.

and they were continuously cored. Completion depths of the six wells ranged from 28.9-36.2 feet bgs. All groundwater wells, except G4, were originally to be completed to the bottom of the aquifer. However, no cores from the demonstration site were available prior to drilling, resulting in misplacement of screened interval for well G5. Well G6 was installed as a replacement for G5 (although G5 was still used and sampled) at the correct screened depth of 31.6-29.1 feet bgs. The remaining screened intervals are all in the permeable portion of the aquifer, with G3 and G6 at the bottom of the permeable gravel (29-31.5 feet bgs) and G1, G2, and G4 in the middle and upper portions of the aquifer (25.5-29 feet bgs). G1 and G2 were supposed to be at the same depth as G3, but the CPT rig could not drive them any deeper due to coarse gravel encountered at 29-30 feet bgs. Wells G3 and G6, which were installed by hollow-stem auger, had annular fill consisting of sand, bentonite, and cement grout because of the larger borehole diameter. The other wells were completed with near-surface cement grouting. A concrete pad was added later for the groundwater and vadose zone well monitoring system.

The tracer injection wells and five of the groundwater monitoring wells (all but G5) were screened in the aquifer and required development. However, G2, G3, and G6 were only partially developed. Initially, none of these wells would produce a significant amount of water, and their water levels would recover slowly following pumping. Water flushing eventually improved the sustainable pump rate in G6 to 200 ml/min.

2. Electrode and Vent Well System Installation

Six electrodes (Zone 1 to Zone 6) in a hexagonal array and a central vent well (Zone N) were installed by the Walton corporation using the hollow-stem auger. The six electrodes have 5-feet screened intervals extending from 20-15 feet bgs. The vent well has a 10-feet screened interval from 20-10 feet bgs. All electrodes were originally to be completed to the bottom of the aquifer, which was thought to consist of a clay contact at 40 feet bgs. The actual clay contact was at 33.5-33.8 feet bgs. With the water level at about 25 feet in depth as originally estimated, and the bottom of permeable sediment at 28.5-31.5 feet, the effective aquifer is only about one third of its original estimated thickness of 15 feet. Based on this new information, the total length of the electrode was reduced to 35 feet.

The electrode and vent wells were completed with graphite and sand pack in accordance with the test plan (see Figures 4 and 5). Complications in the addition of graphite to Zone 6 occurred, resulting in its re-installation, with roughly 300 pounds of graphite left in the borehole from the initial installation. However, the extra graphite did not prevent setting the electrode at the correct depth. An annular, insulating casing was placed over each electrode from the ground surface to the filter pack. The wells were completed with the addition of bentonite and cement grout and a troweled, 12-inch diameter cement grout ring on the surface.

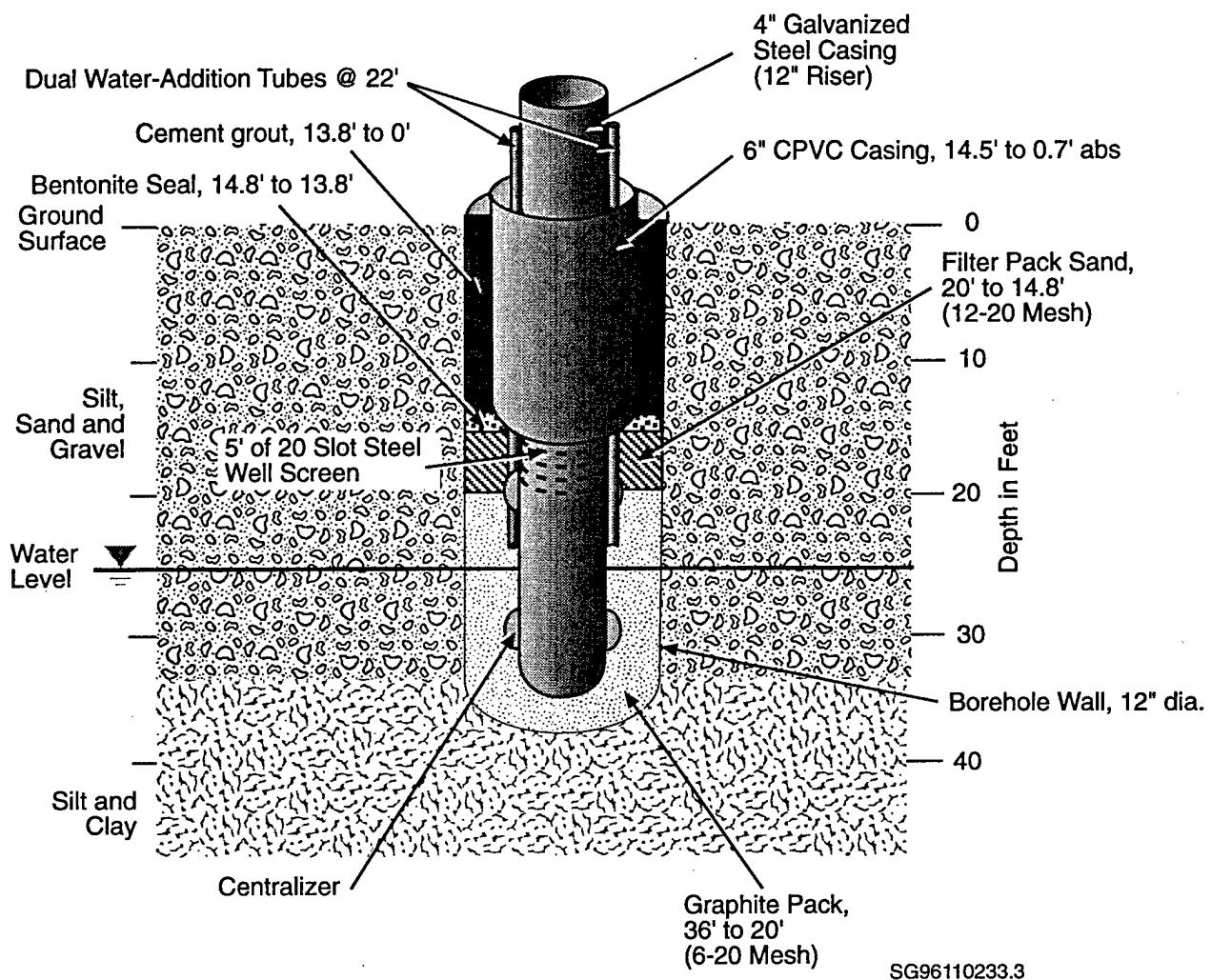


Figure 4. Typical Electrode Installation As Built.

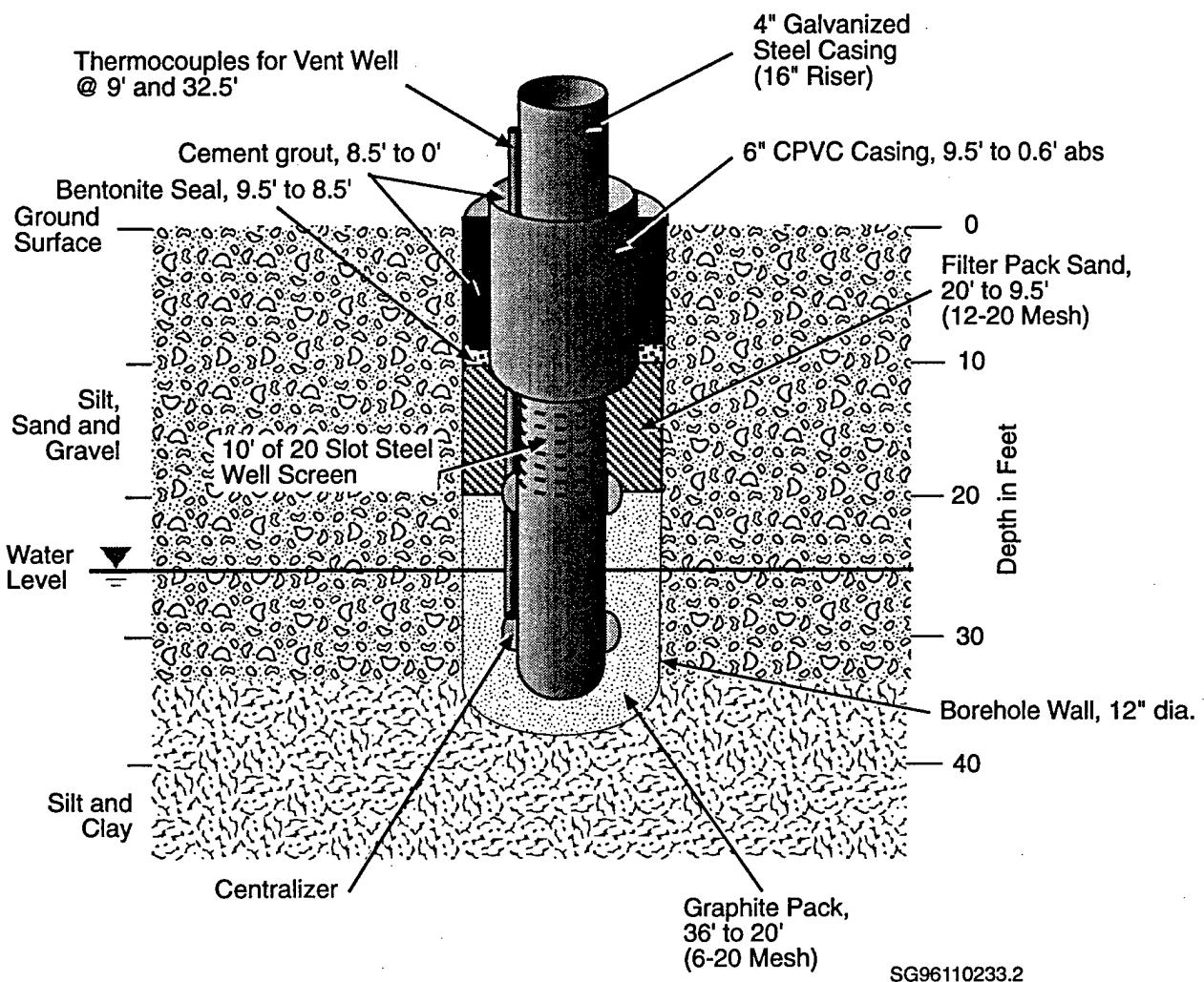


Figure 5. Vent Well Installation As Built

Subsurface installation was completed on October 7, 1996.

3. Above-Ground Equipment Installation: Venting System

Installation of the above-ground venting system began on December 2, 1996. The venting system consisted of a condenser, knockout box and pump, blower, granulated activated carbon (GAC) to treat the off gas, granulated activated carbon to treat the condensate, and a header system connected to the electrodes and central vent to collect the gases and steam. The header system consisted of 2-inch CPVC piping from the electrodes to a 3-inch main header and 3-inch CPVC piping from the central vent. All lines were insulated, and the water lines from the condenser through the liquid GAC system were heat-traced. Drum heaters were installed on both GAC drums. Each line from the electrodes and central vent was valved, and an additional bypass valve was added to the end of the main header to allow outside air to be pulled into the system for better control of the off-gas flow rate, the off-gas temperature, and the vacuum applied to the subsurface. With the exception of the final connection to the blower, installation of the venting system was completed December 8, 1996.

4. Above-Ground Equipment Installation: Electrical System and Instrumentation Connection

Due to the need to first provide a power drop from Dover AFB, the above-ground installation of the electrical system did not begin until January 28, 1997. The six-phase transformer was connected to the base high voltage electrical supply by base support personnel. The 480-V electrical supply for the condenser and blower was provided by a step-down transformer within the six-phase transformer supply.

Instrumentation, including pressure sensors at V2 and V3 and a flow sensor and pressure sensor on the off-gas line, was installed and connected to the data acquisition system (DAS). Additional instrumentation connected to the DAS included thermocouples from the temperature wells and monitors from the six-phase transformer (voltage, amperage, power).

The gas chromatograph (GC) was installed with an on-line sampling point upstream of the gas-phase GAC. The GC was placed in an enclosure to protect it from weather. A second computer system collected information from the GC. An office trailer housed the transformer control computer and the GC data acquisition computer.

The water addition system was also installed. This system included a pump, rotameters, drip tubing to the electrodes, and a tank filled with potable water. The water addition system was not used during operation, because it was not needed. Equipment installation and checkout were completed February 7, 1997. Figures 6-10 show photographs of the installed system.

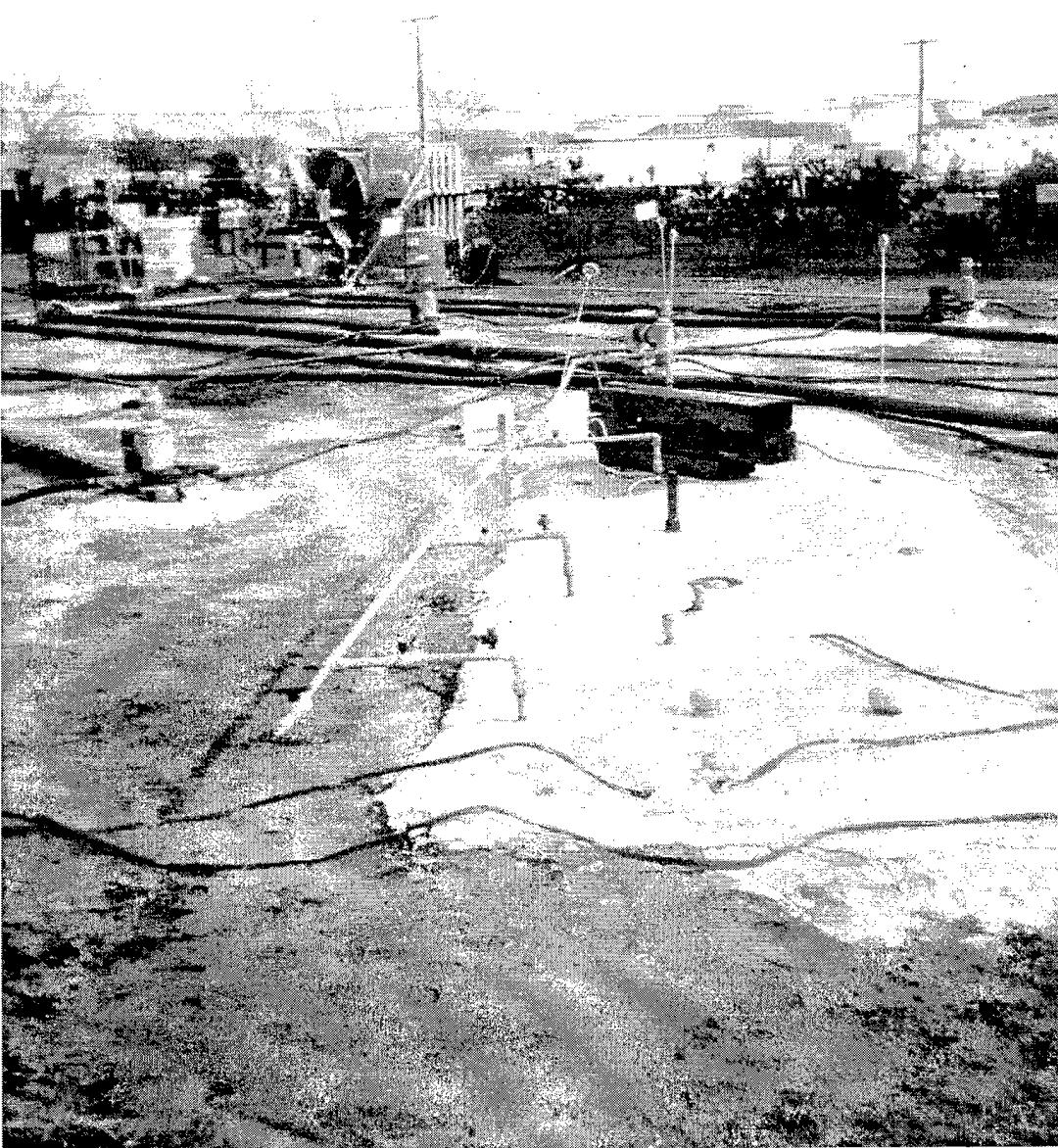


Figure 6. Groundwater and Vapor Sampling Wells.

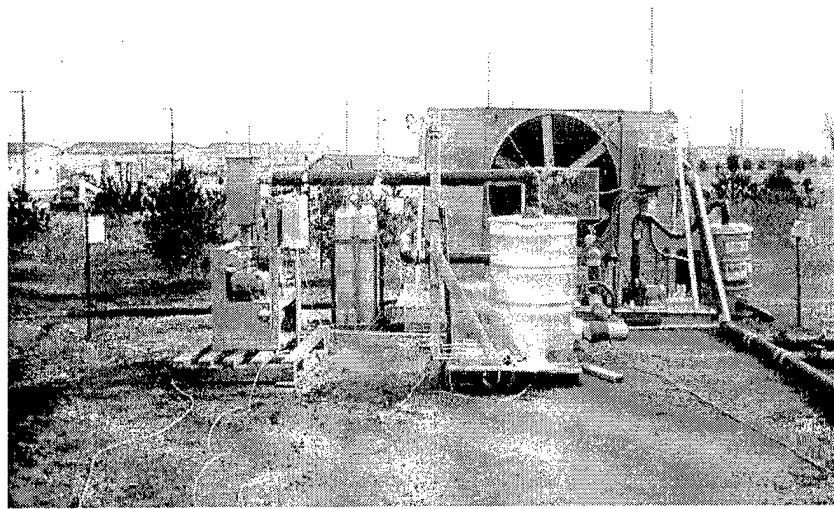


Figure 7. Soil Vapor Extraction System.

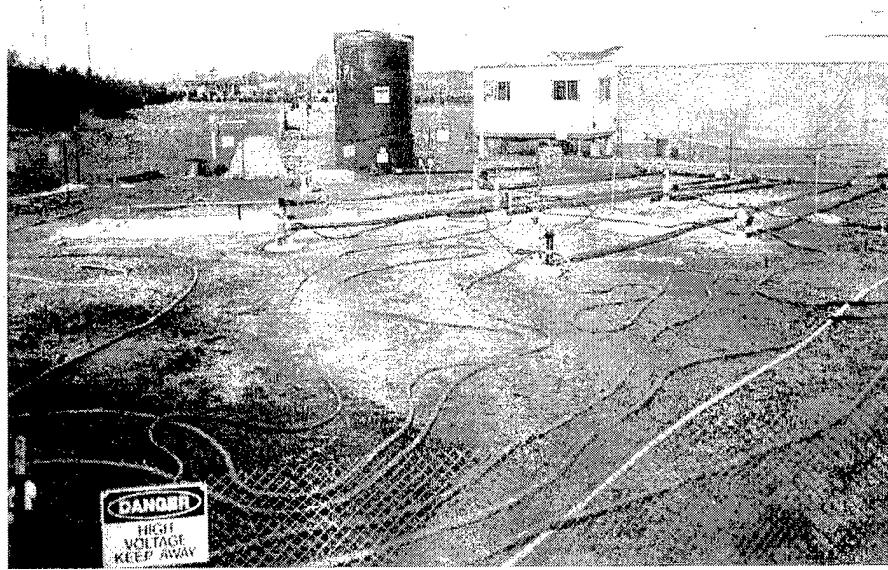


Figure 8. Six-Phase Soil Heating Site Looking North.

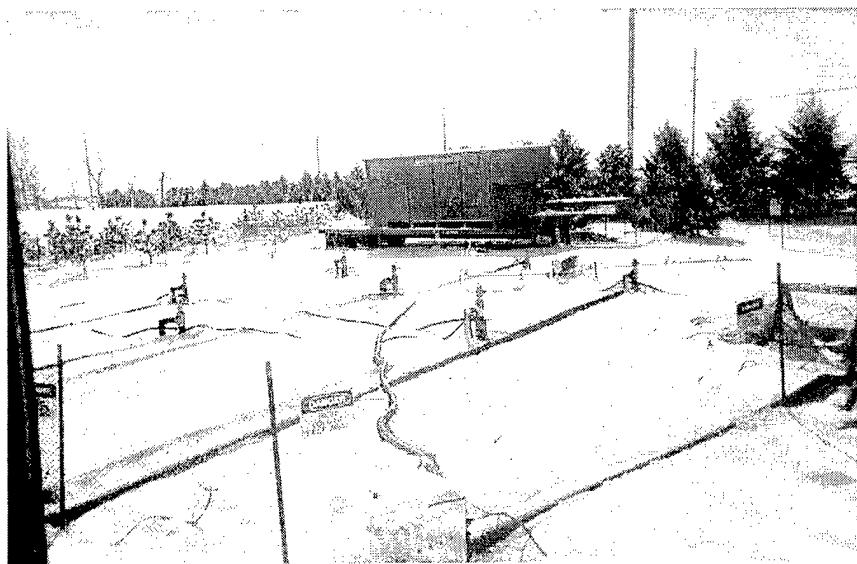


Figure 9. Six-Phase Transformer and Electrodes.

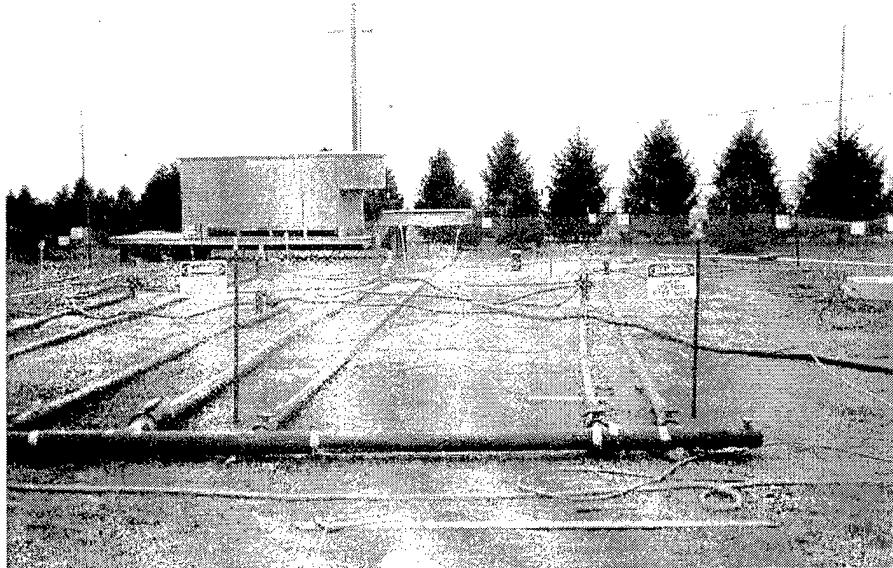


Figure 10. Vapor Extraction Header.

C. TREATMENT SYSTEM OPERATION

Heating operations began on February 7, 1997, on a 24-hour/day basis and were completed March 9, 1997. Daily operations included recording process data, sampling the off gas (four times a day, typically) and adjusting system vacuum. The vadose zone wells and groundwater wells were sampled every other day beginning February 16, 1997. Other routine operations included the collection of quality assurance samples, as outlined in the test plan. In general, both the central vent and the electrode vents were used for vapor extraction throughout the operation. Typical soil vacuum levels were 3-6 inches H₂O at the pressure wells P1 and P2 (vadose zone wells V2 and V3), resulting in off-gas flow rates of 80-120 standard cubic feet per minute (SCFM). Typical applied voltages were 900 V per phase, with a total applied power of about 400 kW.

Transformer operation was generally very smooth. The only failure in the transformer operation was a blown fuse on Phase 3 that occurred February 26, 1997. The fuse was replaced, and the power was restored to that phase March 4, 1997. System operation continued on the other five phases during the interim.

The condenser also functioned well; however, the knockout box and condensate pump experienced several difficulties. On numerous occasions, the pump failed to remove the condensate from the knockout box, causing it to overflow into the air phase GAC. The two primary causes for this failure were freezing of the pump or downstream condensate lines and ineffective condensate pump operation. The condenser and knockout box were existing equipment used for a demonstration in 1993 and were not specifically obtained for this project. The original pump for this system was replaced in the field, because its impeller became blocked with cuttings from construction. The replacement pump was not fully adequate and lost prime (or had insufficient head) when a higher vacuum was applied to the venting system.

The vacuum blower also functioned well, but water carryover during upsets of the condensate removal system occasionally caused the inlet filter to plug. It then had to be vacuumed out and the filter replaced.

While hourly autosampling of the process off gas began as soon as power was turned on, the upset of the condensate removal system on the night of February 11-12, 1997, flooded the off-gas system with water and granular activated carbon, contaminating several key components of the field gas chromatograph. Carbon is of particular concern for the analytical equipment, because it retains organic compounds.

Initially, it was thought that the contamination in the GC was limited to the sample loop and vacuum pump lines. The vacuum pump had failed and was replaced. The sample loop was flushed clean with methanol and reinstalled. The tubing from the outlet of the detector to the vacuum pump was left in place, because contamination there would not affect the analytical results. The GC was restarted and appeared to be giving meaningful results. However,

subsequent attempts to recalibrate the GC revealed that it was not functioning properly. Once the malfunction was recognized, grab samples of the off gas were taken from the same sampling point and analyzed using the gas chromatograph in the Armstrong Laboratory facility. However, this delay in recognition resulted in a loss of off-gas and soil vapor sample analyses from February 12-17, 1997.

Equipment was demobilized from the site starting March 11, 1997, and demobilization was completed March 13, 1997.

D. SAMPLING STRATEGY

1. Approach

The objectives for this demonstration were developed to assess SPSH performance in removing DNAPL contamination. TCE and PCE are common DNAPL contaminants at many Department of Defense sites requiring environmental restoration. However, the subsurface in this initial demonstration was uncontaminated. Instead, two tracer compounds were injected into the aquifer, PMCH and PTMCH. These tracers mimic TCE and PCE in their physical properties but are nontoxic and nonhazardous.

These tracers were used to meet the test objectives to quantify the total tracer mass removed by the process and to determine the effectiveness of liquid and vapor migration control and recovery during the process. While the total mass of tracer removed during the demonstration was quantified, the primary objective was not to perform a complete mass balance or to quantify the fraction of contaminant that could be removed. As stated in the test plan, the limited amount of material injected makes such a mass balance difficult. Rather, the objective of the tracer injection was to assess the potential for vapor and liquid migration of contaminants.

A primary concern during SPSH remediation is adverse mobilization of target compounds in the subsurface. Potential adverse mobilization pathways exist through the liquid water (aqueous), non-aqueous liquid (NAPL), and gas phases.

- Contaminants may dissolve into the aqueous phase and be transported by convection due to thermally induced buoyancy and diffusion.
- If a NAPL exists, it may move through the soil in response to gravity, moderated by the contaminant's viscosity and surface tension.
- Once evaporated, a contaminant in the vapor phase might escape capture due to ineffective soil venting.

The goal of the tracer study was to address these pathways and evaluate the overall effectiveness of migration control and recovery. The strategy for the tracer study was to inject two tracers into the treatment region, one tracer inside the array at a point 0.5 radii from the array center and one outside the array at a point 1.4 radii from the array center (the boundary of

effective heating). Groundwater (liquid phase) and soil vapor (gas phase) samples were taken from screened wells near the injection points. The injection locations and sampling wells are shown in Figure 3. The wells were located radially inward toward the central vent or radially outward. The injection and sampling wells were also aligned with the prevailing groundwater flow, making them either directly up or down gradient of the tracer injection points.

Aligning the wells in this way puts them in the expected pathways of tracer migration. One would expect the primary pathway for aqueous- or DNAPL-phase migration to be either down gradient (migration due to the prevailing groundwater flow) or toward the electrodes (migration due to buoyancy-driven roll cells in the aquifer). The primary pathway for gas-phase migration driven by soil vapor extraction would be radially inward, toward the central vent. While most of the groundwater wells were screened at the bottom of the aquifer, one well (G4) inside the array was screened near the top of the aquifer to assess vertical DNAPL migration. Finally, the use of two unmixed tracers "tags" the origin of each tracer material as either inside or outside the array. Therefore, they can be used to determine the distance the tracer has migrated. In particular, the appearance of the inner tracer at an outer well would indicate poor migration control. One would also expect the tracers to appear sequentially in off gas samples, since the soil inside the array heats more quickly than that outside the array.

2. Sampling and Analytical Methodology

The test plan described the sampling procedures in detail. Because of the breakdown of the field GC, some modifications to the analytical methods were necessary, and grab samples were taken of the process off gas rather than autosampling. The GC used for analyzing all of the samples was the instrument in the Armstrong Laboratory facility, a Hewlett Packard 6790 with an electron capture detector.

To analyze the gas-phase samples, 100 microliters were withdrawn from a Tedlar sample bag with a gas-tight, valved syringe and immediately shot onto the column. The liquid-phase samples were analyzed using a head-space method as described in the test plan. Calibration methods are discussed in the section on QA results below.

3. Data Needs

The data needed to assess mass removal are the amount of each tracer initially injected and the cumulative amount of each tracer recovered in the off-gas treatment system. As described in the test plan, a dual approach to measuring cumulative tracer recovery was originally designed. Off-gas sampling by gas chromatography (combined with the off-gas flow rate) was to provide one measure, while post-test sampling of the off-gas GAC canisters was to provide another estimate. However, the repeated flooding of the vapor-phase GAC canister during failures of the condensate removal system made the GAC data highly unreliable.

To assess migration control, the data needed are simply the presence and relative concentration of each tracer in a particular soil vapor or groundwater sample.

4. Operation

The two tracers were injected into the aquifer on February 6, 1997 at approximately 6 p.m. Table 2 shows the amount of each tracer injected and the injection location. Heating commenced at 3 p.m. the next day.

TABLE 2. TRACER INJECTION AMOUNTS AND LOCATIONS.

Tracer	Amount Injected, g	Injection Location
PMCH	966	B (outside array)
PTMCH	963	A (inside array)

Samples of the process off gas, groundwater, and soil vapor were taken before tracer injection to check for background contaminants or chromatographic interferences with the analytes. A significant peak associated with air appeared in the off gas and soil vapor chromatograms, but it eluted after less than a minute and, therefore, did not interfere with the tracer peaks, which eluted after five or six minutes. No interferences were found in the groundwater analyses.

After heating began, a regular routine of process off gas, soil vapor, and groundwater sampling began, including QA samples. Off-gas samples were taken about 4 times a day. The vadose zone wells and groundwater wells were sampled every other day beginning February 16, 1997. However, some of the off-gas and soil vapor analyses were lost due to the malfunction of the field GC. Section IV-B discusses the results of this sampling and analysis.

E. QA RESULTS

As outlined in the test plan, measurements were taken to assure that data generated during the course of the demonstration were of an acceptable and verifiable quality and that a sufficient number of critical measurements were taken for proper data evaluation. As part of the Quality Assurance Project Plan (QAPP), standards, duplicates, and blank samples were prepared and analyzed in accordance with the test plan. This section summarizes the results of quality assurance (QA) sampling. The raw data for the QA samples is in Appendix A.

Standards. Calibration standards were prepared for both aqueous- and vapor-phase samples. Due to the low solubility of the tracers in water, aqueous calibration standards were

prepared by first dissolving the tracers in a small amount of methanol, making them miscible in water. Aqueous-phase calibration standards were prepared in each decade of the range of 1 to 1000 ppb for each tracer. The resulting calibration curves were linear except at the limit of very low (<1 ppb) concentration. (That is, there was a small, positive offset.)

Vapor-phase standards were prepared in Tedlar® bags. To prepare the dilute standards, a more concentrated standard was made by adding microliter quantities of neat liquid tracer to two liters of nitrogen, allowing the liquids to evaporate, and then diluting the concentrated standard. Vapor-phase calibration standards were prepared in each decade of the range of 1 to 10,000 ppbv. The resulting calibration curves were similarly linear. Both the aqueous- and vapor-phase standards were used to calibrate the gas chromatograph in the Armstrong Laboratory facility for samples of their respective types.

Because matrix spike samples were not taken during the demonstration, the data quality for accuracy must rely on the GC calibration. Percent recovery was not reported.

Blanks. Several types of blank samples were prepared and analyzed. Blanks are designed to detect the introduction of contamination or other artifacts into the sampling, handling, and analysis process. The extent of contamination and the effective detection limits can be determined from this information.

All of the samples were analyzed on the Armstrong Laboratory facility's gas chromatograph. A particularly important type of equipment blank was simply to inject air into the GC using syringes dedicated to the project. These syringes would occasionally become contaminated with the tracer compounds because of their high concentrations in the vapor-phase samples. "Air blanks" were used to detect this contamination, sometimes as frequently as once per primary sample analyzed but at least every one or two days based on operator judgement. When contamination was detected in this manner, a clean syringe would be acquired and used for subsequent analyses.

Field blanks are equivalent to obtaining a background reading at the sampling site by filling a sample container in the field with water or air known not to contain the analyte. This background reading also includes the measurement "noise" inherent in the analysis method. Equipment blanks are used to assess sampling equipment contamination and are created by filling a sample container with uncontaminated water or air in the laboratory.

Table 3 shows the apparent concentrations of the tracer compounds in field and equipment blank samples as measured by the presence of gas chromatography peaks at the correct elution times. A value of zero denotes that no peak was discerned above the background noise of the GC.

TABLE 3. APPARENT TRACER CONCENTRATION IN FIELD AND EQUIPMENT BLANKS

Sample Type	Field Blanks		Equipment Blanks	
	PMCH, ppb	PTMCH, ppb	PMCH, ppb	PTMCH, ppb
Vapor phase	0	4	3	0
Aqueous phase	0	0.02	0	0.02

Based on these values, the detection limit for process off gas and soil vapor is approximately 4 ppbv for each tracer, while about 0.02 ppb is the detection limit for each tracer in groundwater. Note that up to 0.02 ppb of PTMCH was found in the first set of primary groundwater samples, which were taken before tracer injection, and hence were also effectively blanks. However, the actual aqueous phase detection limit may be higher than 0.02 ppb. When the first sets of samples and blanks were analyzed, the GC was set to accept the validity of very small peaks, and so dozens of small peaks at the noise level of the instrument appeared in the chromatograms. It is likely that the peaks that sporadically appeared in chromatograms at the approximate elution time of PTMCH were simply instrument noise. Subsequent adjustment to the gas chromatograph's "noise" level to reject the many spurious peaks also rejected the peak that appeared at the PTMCH elution time. After that adjustment, the tracers were not detected in either the primary samples or in the blanks.

Calibration standards showed that 1 ppb of each tracer was clearly detectable in the aqueous phase. The actual detection limit for the tracers in the groundwater was on the order of 0.1 ppb. However, the highest tracer concentration ever measured in a sample was 0.16 ppb with the vast majority of samples having concentrations less than 0.05 ppb and no samples showing tracer peaks at all after the adjustment to peak area rejection. We infer from these data that the "tracer" peaks in the early analyses were simply noise and that no significant quantity of tracer was ever detected in the groundwater samples or aqueous phase blanks.

Duplicates. Duplicates of each sample type (off gas, soil vapor, and groundwater) were taken at a frequency of 5 percent of the total number of samples. Duplicates allow an assessment of the precision, or repeatability, of a measurement. Precision is expressed as relative percent difference (RPD), as determined by the following equation:

$$RPD = (C_1 - C_2) \div [1/2 (C_1 + C_2)] \times 100 \quad (1)$$

where C_1 is the larger of the two observed values and C_2 is the smaller. Table 4 gives the RPDs for the vapor-phase samples. Note that for this calculation, duplicate analyses of vapor samples that were below the detection limit of 4 ppb were not included, because the differences between these very small numbers resulted in very high RPD values that are not truly significant. As discussed above, none of the aqueous-phase samples were above detection limits, so no RPD is reported for them.

TABLE 4. PRECISION OF SAMPLES TAKEN DURING SPSH DEMONSTRATION AS MEASURED BY FIELD DUPLICATES.

Sample Type	RPD (average), %	
	PMCH	PTMCH
Vapor phase	15	13

The final data quality indicator reported is completeness. Completeness describes the number of valid data points collected from a measurement process compared to the number of data that were subjected to measurement:

$$\% \text{ Completeness} = (\text{VDP} \div \text{TDP}) \times 100 \quad (2)$$

where VDP is the number of valid data points and TDP is the number of total data points obtained. The completeness objective for all analytical methods was 90 percent (as required by EPA guidelines). A total of 192 groundwater analyses, 128 soil vapor analyses, and 150 process offgas (grab) sample analyses were completed, for a combined TDP of 470. Of these, up to 24 of the soil vapor analyses and 10 of the off gas analyses are questionable due to possible syringe contamination, for a combined VDP of $470 - 34 = 436$. Therefore, the percent completeness for the demonstration is 93 percent.

SECTION IV

TECHNOLOGY PERFORMANCE EVALUATION

A. PERFORMANCE DATA

1. Soil and Aquifer Heating Measurement

Figures 11-15 show the results of the soil temperature measurements from temperature wells T1-T5. Temperature wells T2 and T3 represent temperatures directly within the heated region. Temperature well T1 represents temperatures at the fringe of expected heating hydrologically up gradient of the array. Temperature well T4 is the same distance from the heated region as T1 but down gradient. Temperature well T5 is an additional 2 feet downgradient of T4 (see Figure 3). Temperature points at 27.5 feet bgs and 32.5 feet bgs represent temperatures in the groundwater. Temperature points at 22.5 feet represent temperatures in the actively heated region of the vadose zone (from 20 feet bgs-25 feet bgs).

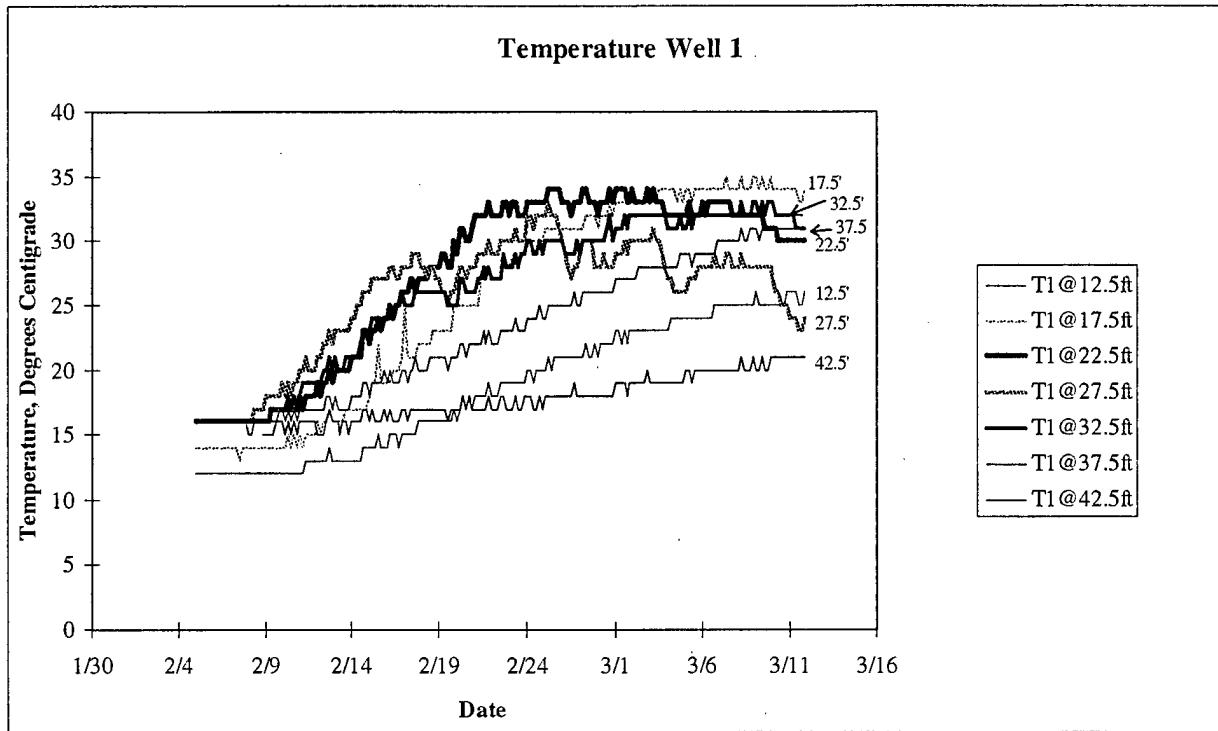


Figure 11. Readings from Temperature Well T1 Immediately Up Gradient from Heated Zone.

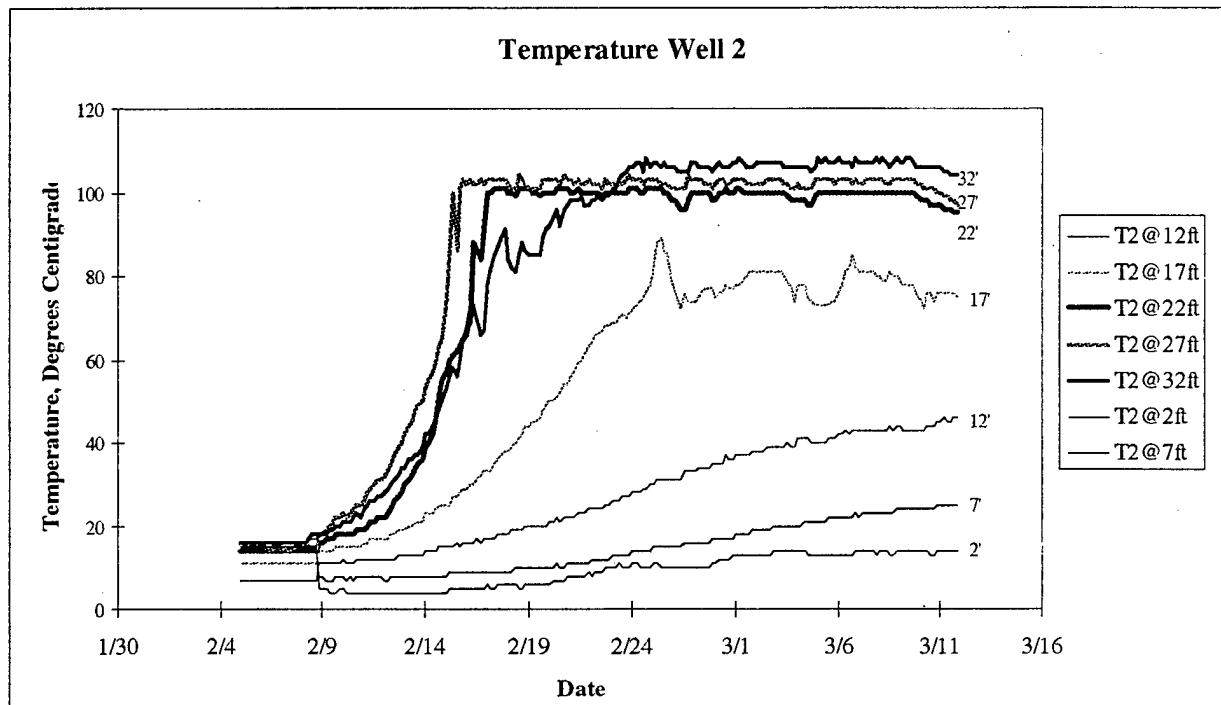


Figure 12. Readings from Temperature Well T2 within the Heated Zone.

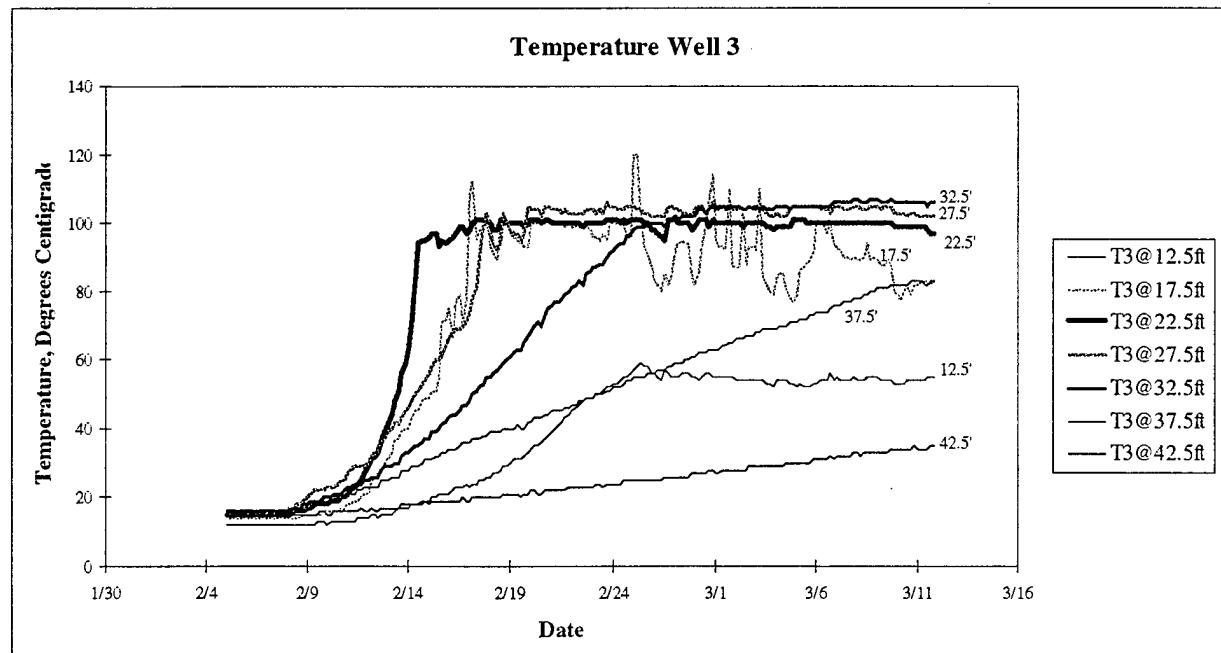


Figure 13. Readings from Temperature Well T3 within the Heated Zone.

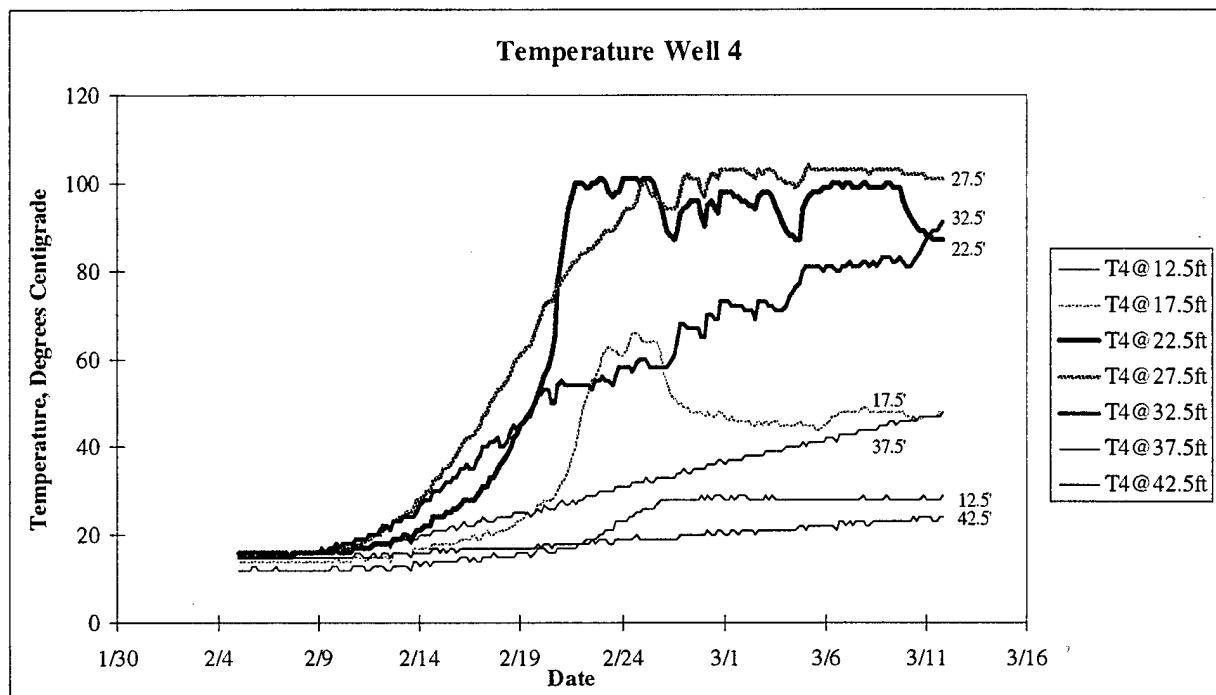


Figure 14. Readings from Temperature Well T4 Immediately Down Gradient from the Heated Zone.

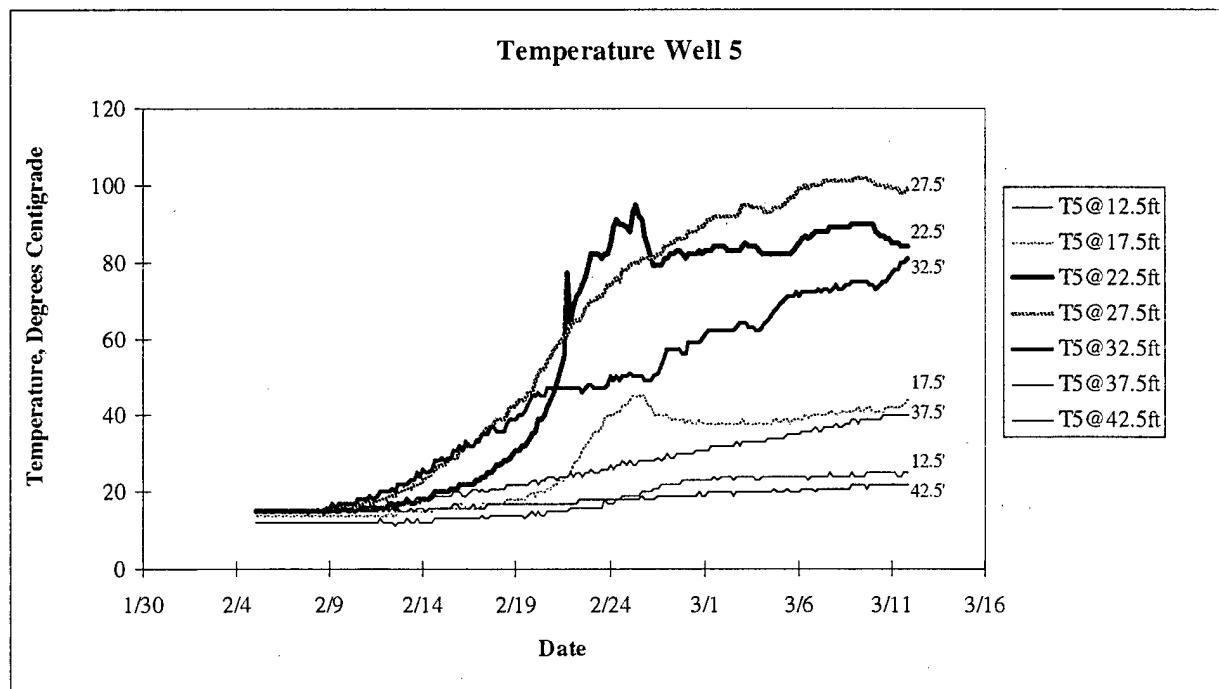


Figure 15. Readings from Temperature Well T5 Down Gradient from the Heated Zone.

Several observations can be made from these data. Boiling temperatures were achieved throughout the saturated zone within the treatment array. Temperature points in the aquifer reached greater than 100°C due to the increased boiling point temperature at the water static head pressure, 105-106°C for the 32.5 feet elevation. These temperatures were obtained within 12-17 days from the start of heating. Figure 16 shows the saturated zone temperatures only. As expected, the groundwater flow created a heat "plume" down gradient of the heated region. Temperature Well T1 immediately up gradient of the heated region showed only modest heating, while T4 and T5 showed significant heating. Temperature Well T4 achieved temperatures >100°C for thermocouples at the 22.5 and 27.5 feet depth.

Temperatures at the 32.5 foot depth heated more slowly than temperatures at the 27.5 foot depth. This is likely due to a thermal buoyancy effect, where the heated water rises and is replaced below by cooler water, causing the temperature in upper regions of the aquifer to increase more quickly.

Figure 17 shows a drop in soil temperature on February 28, 1997, that resulted from an increase in the vacuum applied to the vapor extraction system and hence increased vapor capture. The pressure wells, P1 and P2, were initially kept at approximately 3 inches of water vacuum. When it appeared that the vadose zone temperatures were climbing, potentially indicating a loss of steam capture, the vent vacuum was increased. This caused the vadose temperatures to drop as more steam and air were pulled back towards the electrodes.

2. Tracer Migration and Recovery

The raw data for all the sample analyses are in Appendix A, including QA samples.

Off gas. The concentrations of the two tracers in the off gas from the analysis of the grab samples are shown in Figure 18. Note that power and vapor extraction were off from 1:30 pm on February 18, 1997, until 11:30 am on February 19, 1997. The grab samples corresponding to the first two data points (February 17, 1997, at 4:15 pm and February 18, 1997, at 11:30 am) were taken before this power outage and contained 20-40 ppbv of PTMCH and 0-20 ppbv of PMCH. The next two data points taken after power was restored on February 19, 1997, contained 700-1200 ppbv of PMCH and 300-900 ppbv of PTMCH. Off-gas concentrations of both tracers subsequently rose to several thousand parts per billion and then decayed, with the more volatile PMCH subsiding quickly and the less volatile PTMCH coming out over the next 8-10 days. A second peak in both tracer concentrations appears around March 8, 1997, late in the operation. The validity of those data is currently uncertain. The septa of the Tedlar® sampling bags or the sample injection syringe may have been contaminated at that time.

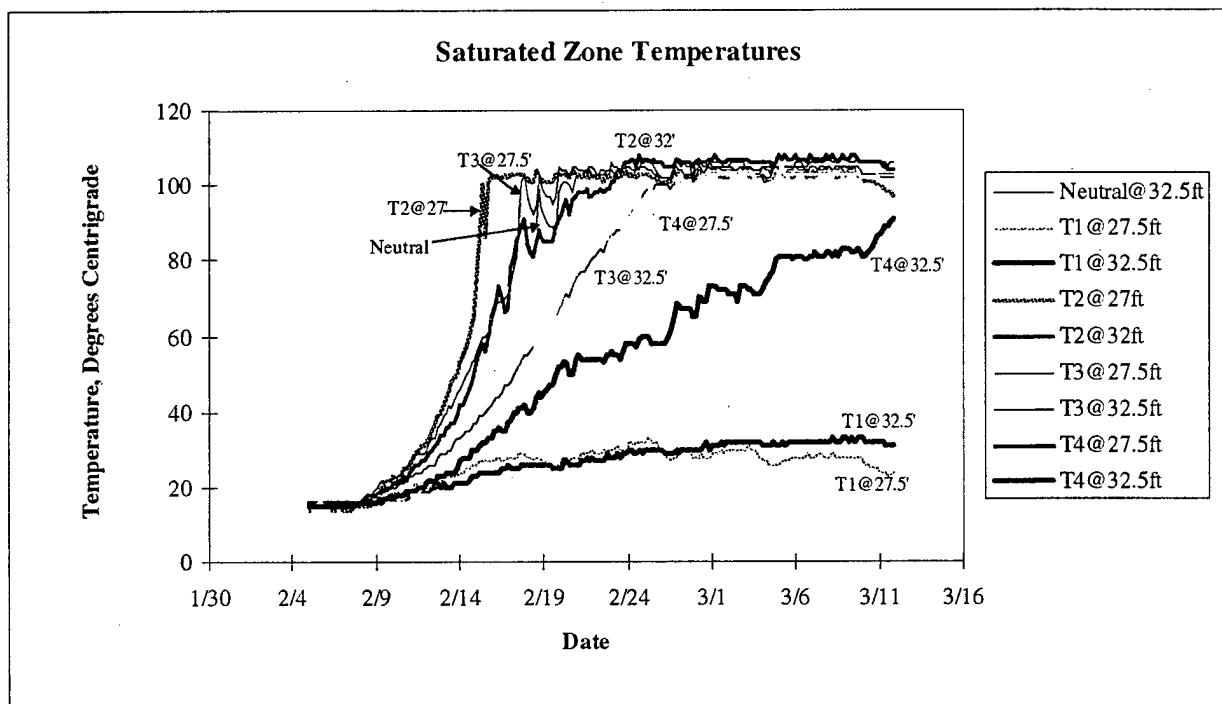


Figure 16. Saturated Zone Temperatures.

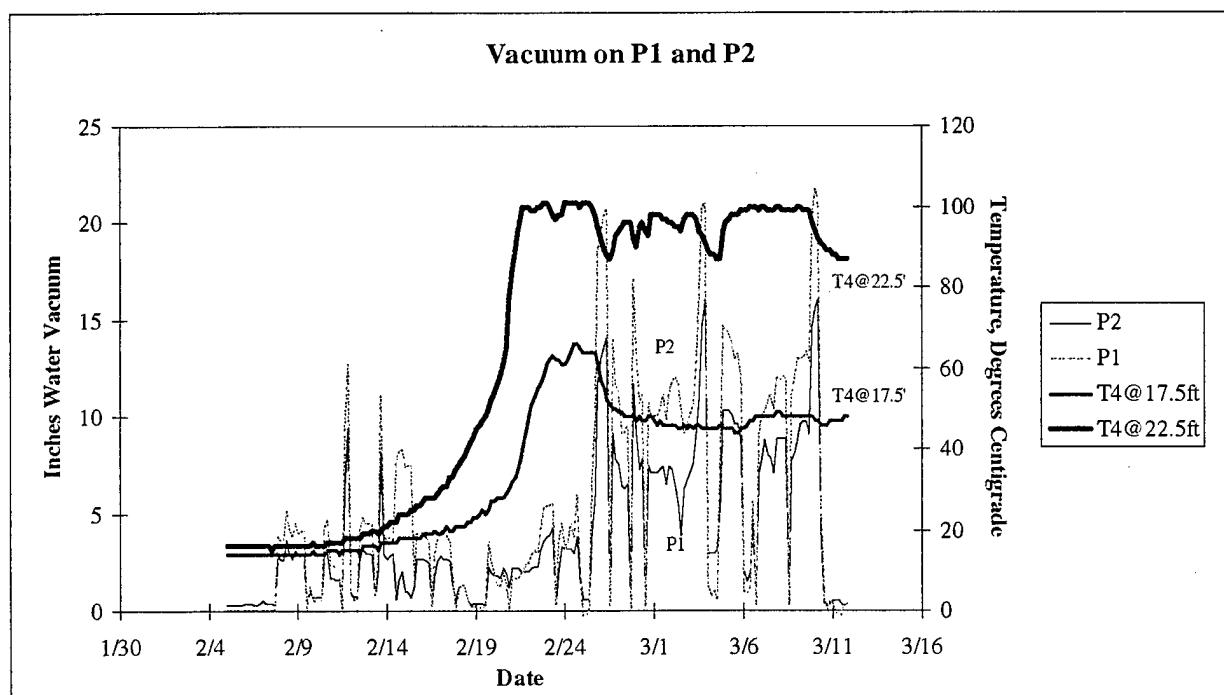


Figure 17. Vacuum at P1 and P2 Compared to Vadose Zone Temperatures on Well 4.

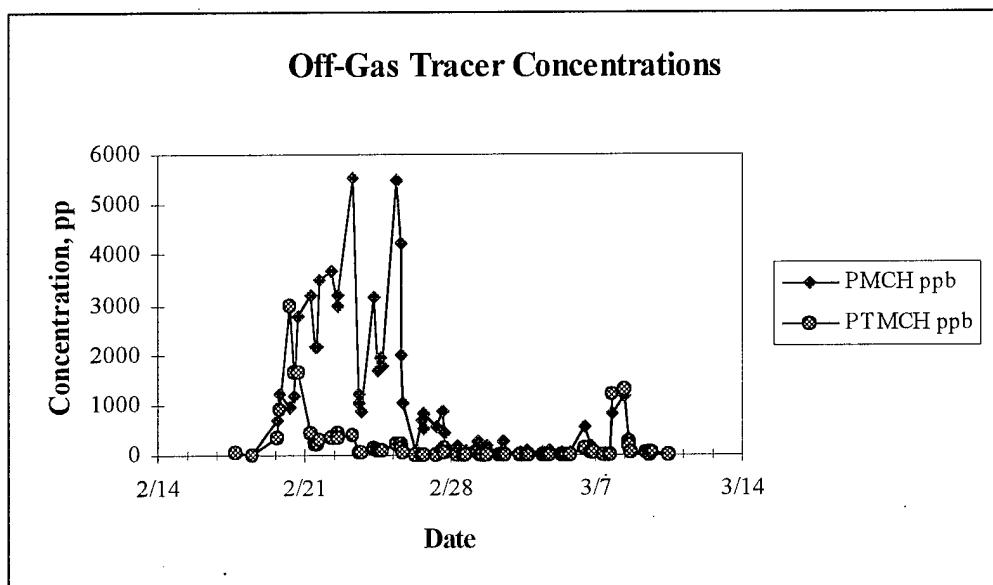


Figure 18. Tracer Concentrations in ppbv in the Off Gas During Six-Phase Soil Heating Operations.

Figure 19 shows the tracer mass collection rate from the process off gases in kg/day vs. time. These values were calculated by multiplying the tracer concentrations by the postcondenser off-gas flow rate at the time of the grab sample. (See Appendix A for further discussion of the calculation method and the raw data.) The collection rates are about 0.1 to 0.3 kg/day during the main period of tracer extraction.

Integrating the collection rates over time yields a rough estimate of the total amount of each tracer recovered from the process off gas. Figure 20 shows the cumulative collection masses. The final amount and percent collected of each tracer, shown in Table 5, was 989 g (102 percent) PMCH and 355 g (37 percent) PTMCH. These numbers decrease to 98 percent and 29 percent, respectively, if the second suspect peak is discounted.

TABLE 5. ESTIMATED AMOUNT AND PERCENTAGE OF TRACER COLLECTED DURING OPERATION

Tracer	Amount Collected, g	% of Amount Injected
PMCH	989	102%
PTMCH	355	37%

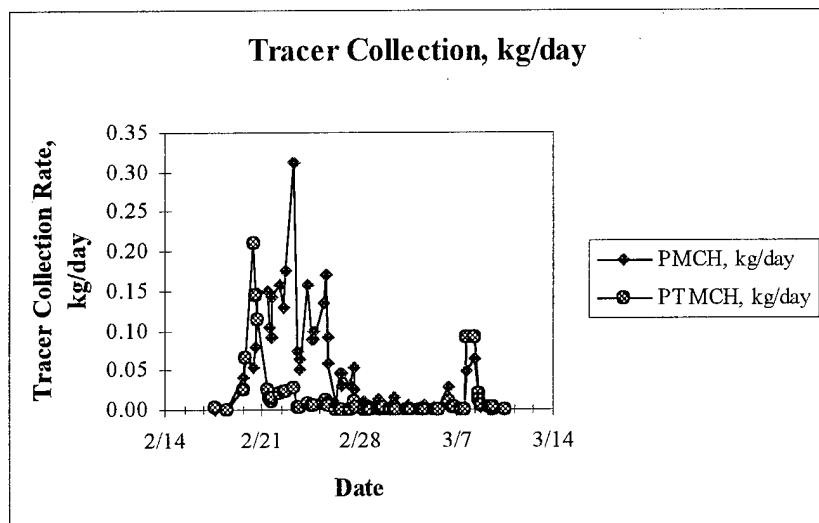


Figure 19. Tracer Collection Rate During Six-Phase Soil Heating Operations.

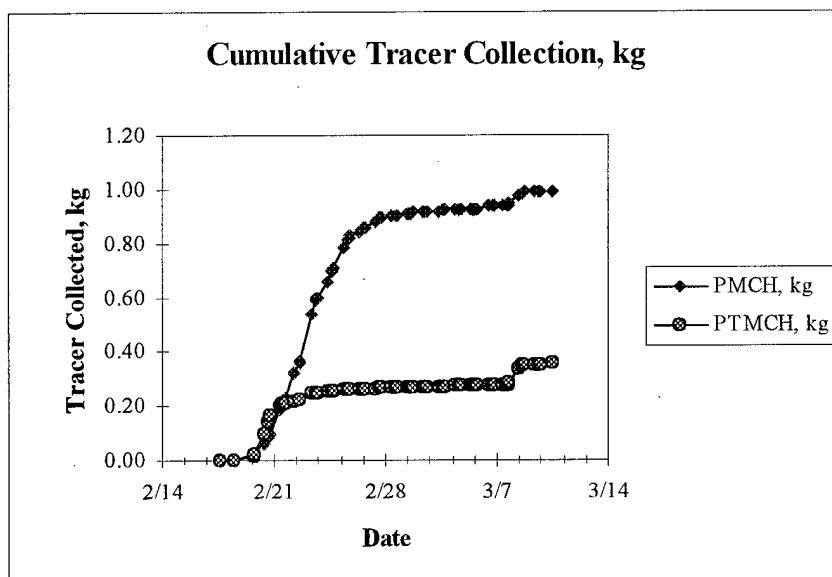


Figure 20. Cumulative Amount of Tracers Collected During Six-Phase Soil Heating Operations.

One of the primary objectives of the demonstration was to quantify the recovery of these two tracer compounds to assess the potential for vapor and liquid migration of contaminants. The mass balance on the PMCH is exceptionally good, perhaps fortuitously so, given the difficulty of making such a balance in typical field operations. The recovery of the PTMCH at 30-40 percent is only fair. However, we do not necessarily interpret this result as implying that two-thirds of that tracer were left in the ground. Four theories regarding the fate of the PTMCH are summarized below.

The PTMCH remained in the aquifer. The PMTCH, the higher boiling point tracer, was injected inside the array near thermocouple well T3. The PTMCH was volatilized very rapidly, coming out over 2 days when temperatures nearby were just starting to approach the boiling point of water. The rapid appearance of PTMCH in the off gas and the subsequent rapid disappearance is inconsistent with a scenario in which one-third of the tracer was volatilized while two thirds remained in the aquifer. An incompletely removed organic compound would show an initial peak followed by a long tail as the remaining material slowly evolved.

The PTMCH remained in the subsurface but migrated out of the heated zone. Elevated concentrations of PTMCH in soil vapor samples at the edge of the heated zone (see below) support this theory somewhat but not completely. During the primary period of PTMCH volatilization, soil vapor concentrations as high as 2300 ppbv were observed at Soil Vapor Well V3 and as high as 870 ppbv at V4. The soil vapor extraction system had been off for nearly 24 hours prior to those measurements, and it is possible that PTMCH vapors migrated outward during that time, recondensing at a colder point in the subsurface away from the center of the array. However, the PTMCH concentrations at those two wells subsequently decreased, oscillating between zero and a few hundred ppbv. Furthermore, since PTMCH volatilization had just begun before the outage, the vapors would not have migrated far before encountering relatively cool soil and recondensing. Therefore, the PTMCH should have been revolatilized later in the heating process. The late off-gas peak around March 8, 1997 (the one with suspect validity) could have been a manifestation of migrated tracer, but both tracers appeared in it. Moreover, the several percent that it contributed to each overall mass balance before disappearing again does not account for the amount of tracer missing.

The PTMCH came out during the data blackout. Because of the loss of off-gas and soil vapor data from February 11-17, 1997, it is possible that some of the PTMCH evolved at that time. In Figure 18, both tracers appear to come out simultaneously. However, since temperatures inside the array (e.g., T2 and T3) were considerably higher than outside the array (T1, T4), it is expected that the PTMCH would come out earlier than the PMCH. This issue is clouded by the difference in the boiling point of the two compounds (76°C vs. 125°C for PMCH and PTMCH, respectively).

The argument against this theory derives from the first two data points shown in Figure 18. These measurements were taken just at the completion of the data blackout but just

prior to the power and vapor extraction outage. Both samples showed low concentrations of both tracers, which is contrary to the theory that most of the PTMCH came out during the blackout.

The PTMCH came out between sampling events. Since its evolution was so rapid, it is also possible that a very large concentration spike of PTMCH came out over only a few hours and was missed by the grab sampling. Note that the two days of PTMCH evolution were just after the 24-hour power and vapor extraction outage. Soil vapor samples (see below) taken just after the power was turned off revealed PTMCH concentrations of 9400 ppbv in the vadose zone near the injection well even though an off-gas grab sample hours earlier had shown only a few tens of ppbv.

None of these theories is completely consistent with the data and our understanding of how SPSH would affect DNAPLs. However, the one that is most supportable and for which there is no contradictory data is that the PTMCH came out between sampling events. This, combined with perhaps some migration (and subsequent soil sorption), appears to be the most likely scenario.

A drum of granular, activated carbon on the off-gas line was meant to provide a second means for estimating the amount of tracer extracted. However, this drum was flooded during the failure of the condensate removal system. Wet carbon is no longer effective in absorbing organic compounds; moreover, much of the carbon was mobilized in the off-gas system and had to be removed.

3. Soil Vapor

As shown in Figure 21, the PMCH was injected outside the SPSH array between wells V3 and V4, with V3 inwards toward the center of the array. The PTMCH was injected inside the array between V1 (radially inward) and V2. Both tracers were injected into the bottom of their respective wells (30-31 feet) by inserting tubing into the wells and pumping the liquid into them. Soil vapor extraction would tend to draw the tracers toward both the central vent and toward the electrodes, where venting was also occurring. Hence, when the soil vapor extraction system is working effectively, one would expect to see:

- Each tracer present in the soil vapor only during the period in which it is observed in the process off gas;
- No PTMCH at wells V3 and V4;
- More PMCH at wells V3 and V4 than at V1 and V2;
- More PMCH at well V3 than V4; and
- More PTMCH at well V1 than V2 when soil vapor removal is primarily through the central vent rather than through the electrodes.

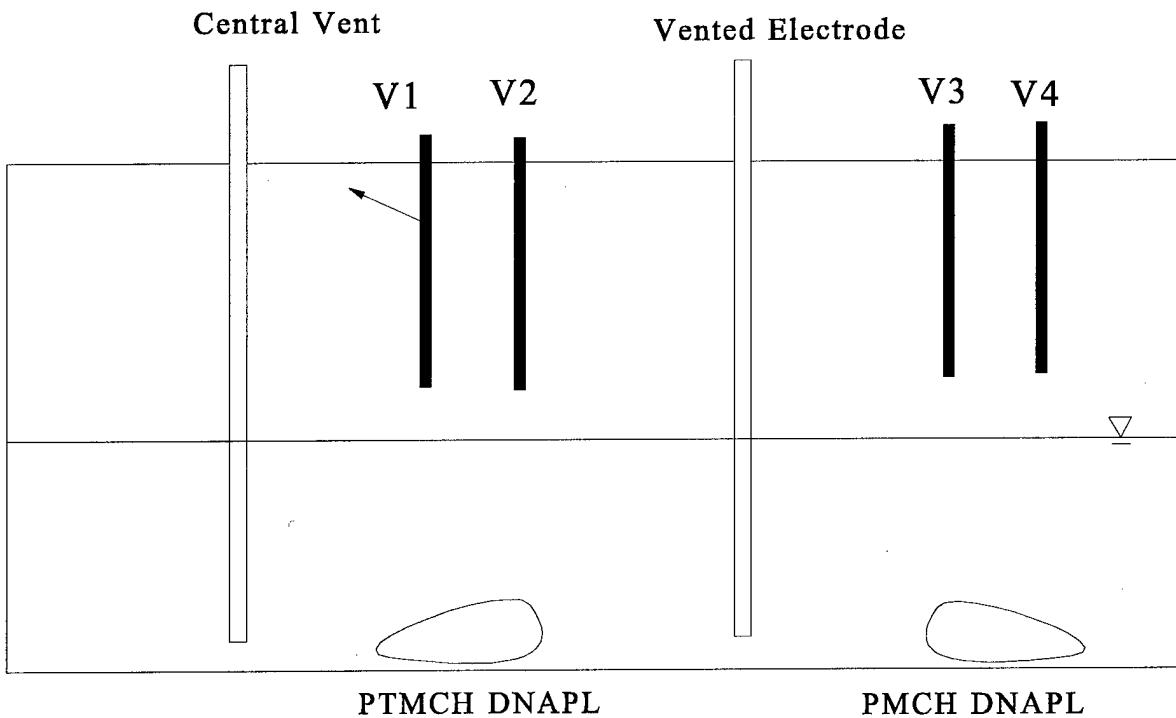


Figure 21. Vertical Cross-Section (Schematic; Not to Scale) of Expected Subsurface Flows Induced by Soil Venting and Relative Positions of Tracers and Soil Vapor Sampling Wells.

Figures 22 and 23 show the PMCH and PTMCH concentrations, respectively, in soil vapor samples extracted from the four sampling wells, V1 through V4. Because two sets of soil vapor samples were analyzed using the unreliable field GC and then discarded, these data are also lost for the period between February 11 and 17, 1997.

Both the PMCH and the PTMCH tended to appear and disappear from the soil vapor at the same time they were observed in the off gas. There was a large PMCH peak on March 6, corresponding to the suspect data in the off gas. Since these samples were handled and analyzed in a virtually identical way as the off-gas grab samples, these analyses may also have been in error. In the earlier portion of operation, PMCH concentrations were far higher at V3 and V4 than at V1 and V2. On February 25, 1997, however, this situation reversed with PMCH appearing primarily at V2 and V1. The V1 concentrations quickly fell again, but high (12,000 ppbv) PMCH concentrations at V2 appeared intermittently. The PMCH concentration at V3 was sometimes, but not always, higher than that at V4. The two values were typically of the same order of magnitude for any given sampling event.

During the primary period of PTMCH volatilization, soil vapor concentrations as high as 2300 ppbv were observed at well V3 and as high as 870 ppbv in V4. However, the soil vapor extraction system had been off for nearly 24 hours before those measurements due to problems with the condensate pump described previously. It is possible that PTMCH vapors migrated outward during that time. The PTMCH concentrations at those two wells

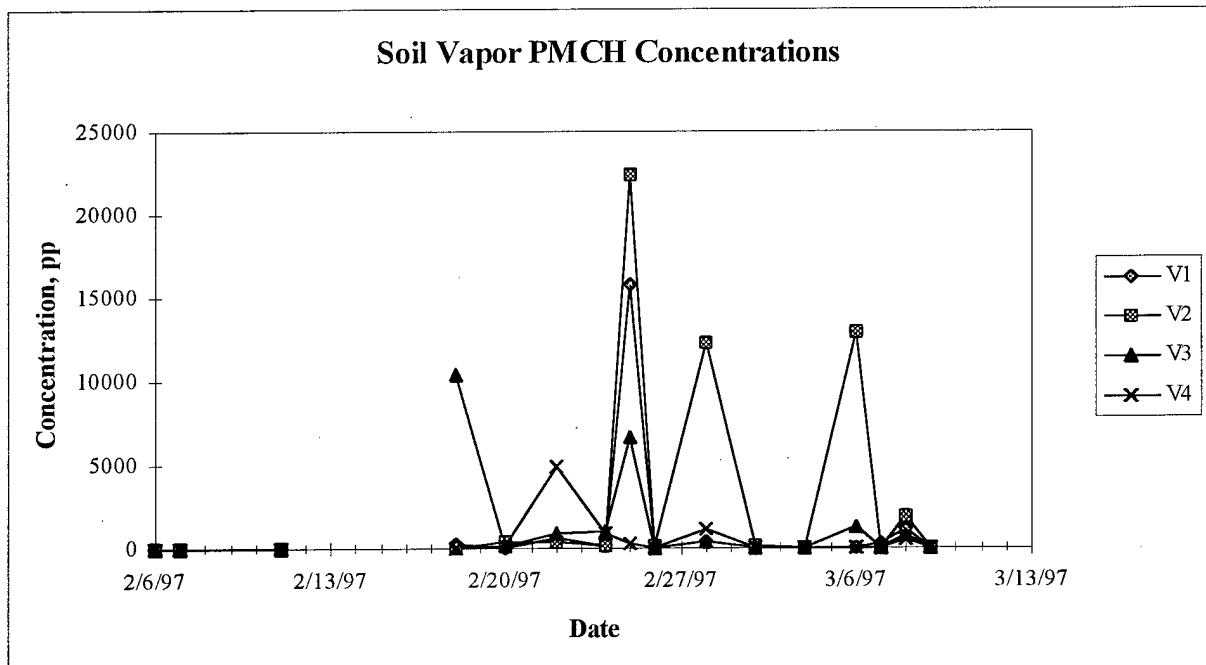


Figure 22. PMCH Concentrations in Soil Vapor from Four Extraction Wells.

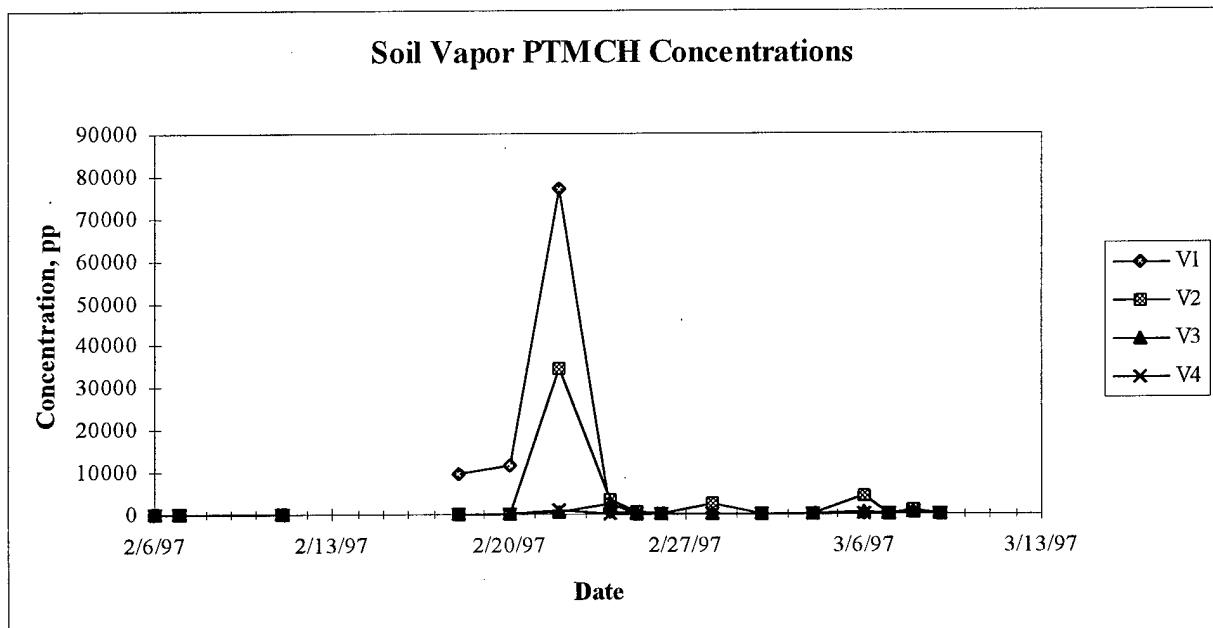


Figure 23. PTMCH Concentrations in Soil Vapor from Four Extraction Wells.

subsequently decreased, oscillating between zero and a few hundred ppbv and staying far below the concentrations at V1 and V2. Neither of the PTMCH concentrations at V1 and V2 was consistently higher than the other.

The soil vapor sampling results suggest that the tracer compounds did migrate outward through the vadose zone to some extent, indicating incomplete control of vapor by the off-gas collection system. This migration may have occurred during the vapor extraction outage on February 18-19.

4. Groundwater

As discussed in Section III-D, analyses of groundwater samples showed no tracer above the detection limits of the analytical equipment. Analysis of the aqueous-phase GAC drum showed no tracer residues from the off-gas condensate.

C. REMEDIATION EFFECTIVENESS

The remediation effectiveness is generally measured by the degree to which contaminants are removed from the site and the remaining soil concentrations meet cleanup criteria. Although actual contaminants were not used at this site, the tracer data can be used to assess these criteria.

As discussed earlier, little if any of the tracer appears to remain in the subsurface, indicating effective remediation. This is borne out by the good mass balance on the PMCH. Though the mass balance on the PTMCH was not as good, no data indicate its continued presence in the subsurface.

D. SYSTEM PERFORMANCE: ENERGY USAGE AND STEAM GENERATION

Over the course of the 30-day test, 200,000 kW-hours were applied to the soil. This energy was used to heat the aquifer and generate steam. The steam was removed through the vapor extraction system and condensed. The total water removed as condensate was 50,000 gallons (49,984). This amount of water is roughly equal to all the subsurface moisture initially in the heated region, assuming a 42-foot diameter zone, 6-foot thick in the saturated zone at 40-50 volume percent moisture and 14 foot in the unsaturated zone at half the moisture content of the aquifer. The energy required to vaporize this water is approximately 119,000 kW-hours, or 60 percent of the total energy used. The remaining energy went into heating the soil and water to the boiling point, estimated at approximately 40,000 kW-hours, and heat losses due to conduction and convection in the subsurface.

Most of the tracer had been removed by February 28, 1997, so additional heating beyond that point produced little incremental results. The total energy used through February 28 (21 heating days) was 136,000 kW-hr, and the total water removed was 29,000 gallons. This represents an energy cost of \$9,500 at \$0.07 per kW-hr or approximately \$16 per cubic meter.

SECTION V

OTHER TECHNOLOGY ISSUES

A. ENVIRONMENTAL REGULATION REQUIREMENTS

Six-Phase Soil Heating is an augmentation to standard soil treatment techniques such as soil vapor extraction or air sparging. As such, it has similar regulatory requirements including air permits for treating contaminated off gas, water discharge permits for discharging treated condensate, and drilling permits. Other potential issues of regulatory concern are the addition of heat to the subsurface and the resulting sterilization of the soils within the treatment zone. Although temperatures will recover to background levels within 6-12 months following treatment, it is unknown how quickly the microbial population will return. A final potential regulatory issue is the addition of water at the electrodes. For some regulatory agencies, this may constitute an "injection"; however, this has not been a concern for most agencies since the water added is typically potable and is recovered as steam.

B. PERSONNEL AND HEALTH AND SAFETY ISSUES

The health and safety issues that apply to SPSH are similar to other insitu removal technologies in terms of potential exposure to contaminants. As in SVE, limited exposure can occur during well installation. Given appropriate capture and treatment of removed contaminants, little additional exposure will occur.

The primary additional hazards associated with SPSH include exposure to electrical hazards and high temperatures. Electrical energy is applied to the ground, and potentially lethal voltages can occur within an exclusion zone. Personnel must be excluded from this zone during operation and appropriate lock and tag procedures used when entering the zone for sampling and maintenance. Appropriate equipment grounding must also be used. Safe operating procedures have been established to ensure that these precautions are taken.

Exposure to high temperature is also a potential hazard. Temperatures of approximately 100°C are obtained within the soil matrix; and, at the surface, electrodes and the surface soils can reach these temperatures as well, causing burns to personnel. Off gas entering the condenser and the condenser surfaces are also hot and are potential burn hazards. The off-gas system operates under a vacuum, so the primary burn hazard is touching exposed hot surfaces.

C. COMMUNITY ACCEPTANCE

As an augmentation to accepted remediation technologies such as SVE, SPSH has generally met with acceptance from the local community. Because SPSH greatly speeds up

remediation, community acceptance is generally favorable. Community concerns relate to exposure to hazardous electrical voltages or electromagnetic radiation and the long-term effect of temperature. Electromagnetic radiation has been measured and shown to be at extremely low levels (significantly less than standard power substations). Temperature recovery is fairly quick (as compared to most remediation time scales) and hence has been of only limited concern.

SECTION VI

ECONOMIC ANALYSIS

A. SITE SCENARIO

The cost and performance of any particular technology is highly dependent on site-specific factors. Therefore, it is necessary to establish a basis when performing a cost analysis or comparison to other technologies (Bremser and Booth 1996). For the purposes of this report, the following site scenario was used to establish this basis.

The site areal extent is 1 acre.

DNAPL exists on an aquitard 40 feet bgs.

Soil from the surface to 40 feet bgs consists of relatively uniform sands.

Groundwater is at 20 feet bgs.

The DNAPL is trichloroethylene.

Electrical power is available to the site (within 400 feet) at 13.8 kV.

Estimated total DNAPL is 0.5 percent of the pore space within the saturated zone.

The total DNAPL is estimated based on the following conceptual ideas Pankow and Cherry 1996). As the DNAPL spreads from the surface, it will "pool" somewhat on the top of the saturated zone and "finger" through the saturated zone until it encounters an aquitard. On the aquitard it can "pool" and exist as 60-80 percent of the pore space. In the regions where it has fingered, it can exist as approximately 30 percent of the pore space, which is the level where the DNAPL exists as separate, discontinuous droplets preventing further downward migration. The pooled regions on the aquitard will continue to spread until they too reach approximately 30 percent of the pore space. Total DNAPL within the saturated region represents approximately 5 percent of the pore space based on fingering, which causes some regions to be highly contaminated and others to be uncontaminated. The regions at the edge of the site will be at much lower concentrations than those in the center giving an overall average of 0.5 percent of the pore space in the saturated zone.

B. COST ANALYSIS

Based on the site scenario, the following technology parameters were established.

Total Treatment Arrays	18
Array Diameter	40 feet
Electrode Depth	40 feet
Heated Region	15 feet bgs to 40 feet bgs
Total arrays treated at one time	3
Total treatment campaigns	6

Weeks per campaign	5 weeks
Total Operation Time	30 weeks
Screened region	10 feet bgs to 15 feet bgs
Air Flow	300 SCFM
Total Contaminant	150,000 lbs (0.5% of pore space for treatment region)

The resulting cost analysis is shown in Table 6. For this particular site scenario, estimated costs are:

Cost per ton of saturated soil treated	\$37
Cost per lb of contaminant removed	\$17
Cost per cubic yard (in situ) treated	\$62

These costs do not include post test characterization and assume that the electrodes can be left in place. These costs may vary by ± 50 percent.

TABLE 6. COST ESTIMATE FOR ONE ACRE DNAPL SITE.

Cost Analysis						
<u>Basis: One Acre Site, 40 ft deep to aquitard, aquifer 20 ft bgs.</u>						
Array #		18				
Electrodes per array		7				
Monitoring points per array		2				
cu ft per ft backfill		1.31				
backfill monitoring wells		0.02				
	Unit	QTY	Unit Cost			
Mobilization	hr	100	\$ 100	\$ 10,000	\$ 10,000	
<u>Subsurface Installation</u>						
<u>Electrode Installation</u>						
4" Diameter Galvanized Well Casing	ft	5040	\$ 30	\$ 151,200		
Graphite 20 ft in 16 in anulus	cu ft	4123	\$ 17	\$ 70,509		
Cement/Bentonite Slurry	cu ft	330	\$ 2	\$ 660		
Sand	cu ft	825	\$ 1	\$ 825		
4" Galvanized Well Screen	ft	630	\$ 55	\$ 34,650		
CPVC 6" pipe	ft	1260	\$ 35	\$ 44,100		
Drilling	day	84	\$ 1,500	\$ 126,000		
Mobilization, driller	ea	2	\$ 600	\$ 1,200		
<u>Monitoring Wells/Sampling</u>						
Samples EPA Method 8240 (VOCs)	ea	288	\$ 250	\$ 72,000		
0.5" CPVC	ft	1440	\$ 1	\$ 1,440		
Thermocouples (4 ea well)	ea	144	\$ 60	\$ 8,640		
Cement/Bentonite Slurry	cu ft	29	\$ 2	\$ 59		
Sand	cu ft	29	\$ 1	\$ 29		
CPT	day	36	\$ 1,000	\$ 36,000		
Mobilization, CPT	ea	1	\$ 600	\$ 600		
<u>Sampling and oversite (geologist)</u>						
travel	ea	1	\$ 1,000	\$ 1,000		
per diem	day	50	\$ 100	\$ 5,000		
TOTAL, SUBSURFACE				\$ 579,112		
<u>Above Surface Installation</u>						
<u>Headers</u>						
2" CPVC	ft	4680	\$ 2.67	\$ 12,496		
3" CPVC	ft	1440	\$ 5.45	\$ 7,862		
2" fittings	ea	432	\$ 6.50	\$ 2,808		
2" female adapter	ea	108	\$ 8.30	\$ 896		
3" fittings	ea	72	\$ 15.00	\$ 1,080		
2" valves	ea	108	\$ 38.50	\$ 4,158		
3" valves	ea	36	\$ 215	\$ 7,740		
Galvanized tee	ea	126	\$ 53.53	\$ 6,745		
Galvanized nipples	ea	126	\$ 2.00	\$ 252		
galv bushings/nipples	ea	252	\$ 12.20	\$ 3,074		
3 by 2 CPVC tee	ea	108	\$ 28.60	\$ 3,089		
3 by 3 CPVC tee	ea	18	\$ 19.11	\$ 344		
3" female adapter CPVC	ea	18	\$ 30.31	\$ 546		
Labor, installation	hr	864	\$ 75	\$ 64,800		
<u>SVE System</u>						
Shipping, blower and ofgas	ea	1	\$ 2,500	\$ 2,500		
Shipping, water treatment	ea	1	\$ 2,500	\$ 2,500		
Shipping, scrubber	ea	1	\$ 2,500	\$ 2,500		
Anemometer	ea	6	\$ 1,500	\$ 9,000		
Pressure Gauges	ea	6	\$ 1,500	\$ 9,000		
Water Totalizer	ea	2	\$ 500	\$ 1,000		
Installation	hr	360	\$ 75	\$ 27,000		
Per diem	day	63	\$ 100	\$ 6,300		
<u>Heating Installation</u>						
Shipping Transformer/cables	ea	1	\$ 5,000	\$ 5,000		
Shipping, condenser	ea	1	\$ 2,500	\$ 2,500		
Water addition tank	ea	1	\$ 3,000	\$ 3,000		
Rolameters	ea	108	\$ 50	\$ 5,400		
Flowmeters	ea	18	\$ 250	\$ 4,500		
Drip tubing	ft	5400	\$ 0.20	\$ 1,080		
Installation	hr	288	\$ 100	\$ 28,800		
Travel	ea	2	\$ 1,000	\$ 2,000		
Per diem	day	39	\$ 100	\$ 3,900		
Electrical Subcontractor	ea	1	\$ 15,000	\$ 15,000		

TABLE 6. (CONTINUED)

TOTAL ABOVE SURFACE				\$ 246,870
TOTAL INSTALLATION				\$ 825,982 \$ 825,982
PERMITTING				
Air permitting	ea	1	\$ 500	\$ 500
Groundwater discharge	ea	1	\$ 2,000	\$ 2,000
Labor	hr	200	\$ 100	\$ 20,000
TOTAL PERMITTING				\$ 22,500 \$ 22,500
START-UP--two weeks				
Labor	hr	160	\$ 100	\$ 16,000
Air Analysis	ea	6	\$ 1,000	\$ 6,000
Water Analysis	ea	6	\$ 250	\$ 1,500
Field GC	week	2	\$ 100	\$ 200
Travel	ea	2	\$ 1,000	\$ 2,000
Per Diem	day	28	\$ 100	\$ 2,800
TOTAL START-UP				\$ 28,500 \$ 28,500
OPERATIONS				
Labor	hr	420	\$ 75	\$ 31,500
Changeover Labor	hr	400	\$ 100	\$ 40,000
Per Diem	day	50	\$ 100	\$ 5,000
Travel	ea	10	\$ 1,000	\$ 10,000
Field GC	week	30	\$ 100	\$ 3,000
Equipment Amortization Cost	week	30	\$ 5,000	\$ 150,000
TOTAL OPERATIONS				\$ 239,500 \$ 239,500
UTILITIES				
electrical energy	kW-hrs	7098667	\$ 0.07	\$ 496,907
supplemental fuel	week	30	\$ 500	\$ 15,000
TOTAL UTILITIES				\$ 511,907 \$ 511,907
DEMOLIBILIZATION				
Shipping, blower and offgas	ea	1	\$ 2,500	\$ 2,500
Shipping, water treatment	ea	1	\$ 2,500	\$ 2,500
Shipping, scrubber	ea	1	\$ 2,500	\$ 2,500
Shipping Transformer/cables	ea	1	\$ 5,000	\$ 5,000
Shipping, condenser	ea	1	\$ 2,500	\$ 2,500
Labor	hrs	200	\$ 75	\$ 15,000
TOTAL DEMOLIBILIZATION				\$ 30,000 \$ 30,000
SUBTOTAL				\$ 1,668,388
Design, Engineering (10%)				\$ 166,839
Management (10%)				\$ 166,839
SUBTOTAL				\$ 2,002,066
Contingency (25%)				\$ 500,517
TOTAL				\$ 2,502,583
Cost per ton				\$ 37
Cost per lb contaminant removed				\$ 17
Cost per cubic yard (in situ)				\$ 62

SECTION VII

CONCLUSIONS

Six-Phase Soil Heating was successful in heating the aquifer to levels sufficient to remove target DNAPL contaminants. Temperatures within the heated region exceeded the target heating temperatures, and boiling occurred throughout the aquifer.

The vapor extraction system collected DNAPL tracers mobilized during heating. The total tracer recovered during heating was approximately 100 percent of the PMCH and 35 percent of the PTMCH. The lower recovery of the PTMCH may be due to a loss of data during a time period when the off-gas GC was not functioning properly or to a high spike in off-gas concentration not detected by intermittent grab samples. Data do not indicate any significant tracer remaining in the soil.

The operation of the SPSH treatment system was relatively robust. The transformer, condenser, and blower all functioned properly. The condensate collection system, however, had numerous difficulties caused by freezing in the lines and a poorly functioning pump. This system should be modified for future demonstrations or deployments.

Groundwater samples showed no measurable tracer at any time during the demonstration.

Soil vapor samples suggest that the tracer compounds did migrate outward through the vadose zone during the demonstration, indicating incomplete control of vapor by the off-gas collection system. This occurred during the initial stages of steaming. When higher temperatures in the vadose zone were observed (indicating incomplete capture of steam), the vacuum applied to the soil was increased. This resulted in lower vadose zone temperatures and more complete capture. The essentially complete capture of the PMCH (which was injected at the edge of the heated zone and was the tracer more likely to migrate) indicates that, in general, the vapor extraction system operated successfully.

The total energy used for the demonstration was 200,000 kW-hour, and 50,000 gallons of condensate were collected from about 800 yd³ (600 m³) of heated soil. Total heating time was 30 days; however, most of the tracer was removed during the first 21 days of heating. During that period, 136,000 kW-hour was used and 29,000 gallons of condensate were collected. At \$0.07 per kW-hour, this represents an energy cost of \$9,500 or approximately 16 dollars per cubic meter heated.

Based on the results of the demonstration, a cost analysis was done for a "typical" DNAPL site. The assumed site conditions were a one-acre site containing a DNAPL perched on an aquitard 40 feet bgs with groundwater at 20 feet bgs. Given this particular site scenario, estimated costs for applying SPSH are approximately 35 dollars per ton, 15 dollars per pound of

contaminant, or 60 dollars per cubic yard (in situ). These numbers should be used with caution, however, since they are highly dependent on site-specific conditions.

SECTION VIII

RECOMMENDATIONS

The goal of the saturated zone demonstration was to determine the feasibility of using SPSH to mobilize DNAPL in the aquifer. The results from the demonstration indicate that the use of SPSH is feasible and that it should be considered for full scale deployment at an actual site.

This recommendation is also supported by other recent data. From October 1996 through May 1997, SPSH was used to remove PCE contamination in a tight clay soil at a site in Chicago. The site was initially believed to be a vadose zone site; however, subsequent investigation indicated that it was actually a perched aquifer, fully saturated up to the ground surface. In addition, the amount of contamination in the site indicated that it contained DNAPL, with concentrations in one array over 3000 ppm.

Six-Phase Soil Heating was successful at removing more than 12,000 pounds of contaminant during treatment (approximately half from a single, extremely contaminated, array) under even more severe conditions than those expected to be encountered at most DNAPL sites. The soil in Chicago was an extremely tight clay soil, entirely saturated to the surface, and next to an occupied building. This successful deployment, in conjunction with the data obtained from the GRFL saturated zone demonstration, indicates that SPSH is a viable candidate for DNAPL remediation.

To deploy SPSH at a DNAPL site, a modification to the off-gas treatment system would be required. A DNAPL site will likely contain large amounts of contaminant. Thermal oxidation or catalytic oxidation may be more economic than carbon adsorption for such large amounts of contaminant. If these destructive technologies are used, then the hydrochloric acid produced may need to be scrubbed.

A more robust condensate removal system is also recommended to allow the SVE system to be operated at higher vacuums. The suction on the condensate pump should be increased. In addition, the heating system should be shut down whenever the off gas system is not operating. This has been standard practice at sites where actual contaminant is present and is readily implemented by an automatic shutdown system.

Installation of the monitoring points by CPT was more difficult than originally anticipated. An appropriate installation method should be selected depending on the site-specific conditions.

(This page is blank.)

REFERENCES

Bergsman, T.M., J.S. Roberts, D.L. Lessor, and W.O. Heath, Field Test of Six-Phase Heating and Evaluation of Engineering Design Code, PNL-SA-21537, Pacific Northwest National Laboratory, Richland, Washington, 1993a.

Bergsman, T.M., J.S. Roberts, D.L. Lessor, and W.O. Heat, Six-Phase Soil Heating to Enhance Removal of Contaminants, PNL-SA-21709, Pacific Northwest National Laboratory, Richland, Washington, 1993b.

Bergsman, T.M., P.A. Gauglitz, J.S. Roberts, and M.H. Schlender, "Soil-Heating Technology Shown to Accelerate the Removal of Volatile Organic Compounds from Clay Soils," Federal Facilities Environmental Journal, Winter 1995/96, pp. 69-79, 1995.

Bremser, J. and S.R. Booth, Cost Studies of Thermally Enhanced In-Situ Soil Remediation Technologies, Los Alamos National Laboratory, LA-UR-96-1863, 1996.

Gauglitz, P.A., J.S. Roberts, T.M. Bergsman, S.M. Caley, W.O. Heath, M.C. Miller, R.W. Ross, and R. Schalla, Six-Phase Soil Heating Accelerates VOC Extraction from Clay Soil. Presented at Spectrum '94: International Nuclear and Hazardous Waste Management, Atlanta, Georgia, August 14-18, 1994.

Heath, W.O., P.A. Gauglitz, G. Pillay, T.M. Bergsman, E.A. Eschbach, S.C. Goheen, R.L. Richardson, J.S. Roberts, and R. Schalla, Heating of Solid Earthen Material, Measuring Moisture and Resistivity, 1996, United States Patent 5,545,803.

Heath, W.O., R. Richardson, S. Goheen, Treating of Solid Earthen Material and a Method for Measuring Moisture Content and Resistivity of Solid Earthen Material, United States Patent 5,347,070.

Pankow, J.F. and J.A. Cherry. 1996. "Dense Chlorinated Solvents and Other DNAPLs in Groundwater," Waterloo Press, Portland, Oregon.

(This page is blank.)

APPENDIX A
TRACER SAMPLING DATA

TRACER SAMPLING DATA

This appendix shows the sample analysis data for the two tracers, PMCH and PTMCH, in process off gas, soil vapor, and groundwater samples. Quality assurance sample results are included. The appendix also shows the calculated values for the instantaneous tracer removal rate and the cumulative tracer removal.

Values of the instantaneous removal rate for each tracer were calculated for every off gas sampling event by multiplying the tracer's concentration by the process off gas flow rate and appropriate factors for converting parts per billion and SCFM to kg/day. However, since the vacuum applied to the soil had to be reduced to enable sampling, the flow rate at the exact moment of sampling would not be typical of operation. We have assumed that the concentration of tracer in the collected soil vapor does not change substantially during the few minutes of reduced vacuum required to sample the off gas. Therefore, the steady off gas flow rate just prior to sampling was used in the calculation. This data would have been acquired no more than 30 minutes earlier.

Cumulative tracer removal amounts for each tracer are calculated by integrating the instantaneous removal rates from point to point using the trapezoid rule. That is, for each interval between samples, the contribution to the cumulative removal is calculated by multiplying the interval ($t_{n+1} - t_n$) by the average of the beginning and ending removal rate values ($[r_n + r_{n+1}]/2$). Each of these contributions is then summed over time, with the cumulative value at any point being the sum of all the contributions up to that point.

As the text pointed out, the level at which a peak on the gas chromatograph was rejected as noise was raised for the groundwater samples analyzed on March 10-11, 1997 compared to the earlier analyses. Since peaks of several hundred parts per trillion were not accepted in these analyses, none of the later results showed detectable levels of either tracer.

Table A-1. Off-gas Sample Analysis and Flow-rate Data

Date/Time	PMCH ppb	PTMCH ppb	Instant- aneous SCFM	PMCH kg/day	PTMCH kg/day	kg PMCH total	kg PTMCH total
2/17/97 16:15	22	42	82.4	0.0011	0.0027	0.0000	0.0000
2/18/97 11:30	0	17	79.6	0.0000	0.0011	0.0004	0.0015
2/19/97 16:30	702	327	96.9	0.0411	0.0246	0.0253	0.0170
2/19/97 18:35	1201	906	94	0.0682	0.0661	0.0300	0.0209
2/20/97 7:45	954	2977	90.7	0.0522	0.2096	0.0630	0.0966
2/20/97 13:40	1149	1638	113.9	0.0790	0.1448	0.0792	0.1402
2/20/97 17:30	2742	1648	88.9	0.1472	0.1137	0.0973	0.1609
2/21/97 7:53	3173	423	77.6	0.1487	0.0255	0.1859	0.2026
2/21/97 12:30	2156	230	79.4	0.1034	0.0142	0.2101	0.2064
2/21/97 16:00	2165	197	69.1	0.0903	0.0106	0.2243	0.2082
2/21/97 17:15	3505	296	67.2	0.1422	0.0154	0.2303	0.2089
2/22/97 7:15	3670	366	71.2	0.1578	0.0202	0.3178	0.2193
2/22/97 14:15	2965	430	72	0.1289	0.0240	0.3596	0.2258
2/22/97 15:15	3205	333	90.9	0.1759	0.0235	0.3660	0.2267
2/23/97 8:00	5537	387	93.6	0.3129	0.0281	0.5365	0.2448
2/23/97 14:40	1191	45	102	0.0733	0.0036	0.5902	0.2492
2/23/97 16:00	1045	37	102	0.0644	0.0029	0.5940	0.2493
2/23/97 17:00	846	35	97.4	0.0497	0.0026	0.5964	0.2495
2/24/97 7:30	3134	120	83	0.1570	0.0077	0.6588	0.2526
2/24/97 13:50	1702	93	87.6	0.0900	0.0063	0.6914	0.2544
2/24/97 16:15	1947	73	83.3	0.0979	0.0047	0.7009	0.2550
2/24/97 18:00	1785	71	81.7	0.0880	0.0045	0.7077	0.2553
2/25/97 9:30	5481	211	40.3	0.1334	0.0066	0.7792	0.2589
2/25/97 15:00	4225	234	66.6	0.1699	0.0121	0.8139	0.2611
2/25/97 16:30	1967	139	77.9	0.0925	0.0084	0.8221	0.2617
2/25/97 18:15	1039	53	94.7	0.0594	0.0039	0.8277	0.2622
2/26/97 7:30	84	10	128.2	0.0065	0.0010	0.8458	0.2635
2/26/97 14:30	712	6	105.9	0.0455	0.0005	0.8534	0.2637
2/26/97 18:00	524	14	92.4	0.0292	0.0010	0.8589	0.2638
2/26/97 19:00	841	17	91.3	0.0464	0.0012	0.8605	0.2639
2/27/97 8:00	571	17	85.1	0.0293	0.0011	0.8810	0.2645
2/27/97 16:00	882	99	99.6	0.0530	0.0077	0.8947	0.2660
2/27/97 17:00	417	127	99.6	0.0251	0.0098	0.8963	0.2663
2/27/97 19:00	115	27	105.4	0.0073	0.0022	0.8977	0.2668
2/28/97 8:00	158	15	102.1	0.0097	0.0012	0.9023	0.2678
2/28/97 16:00	39	21	92.5	0.0022	0.0015	0.9043	0.2682
2/28/97 17:00	91	13	97.7	0.0054	0.0010	0.9044	0.2683
2/28/97 18:00	60	9	91.7	0.0033	0.0006	0.9046	0.2683
3/1/97 7:30	244	29	92.1	0.0136	0.0021	0.9094	0.2691
3/1/97 12:00	196	19	89.4	0.0106	0.0013	0.9116	0.2694
3/1/97 14:00	156	17	88.4	0.0083	0.0012	0.9124	0.2695
3/1/97 17:00	170	20	85.1	0.0087	0.0013	0.9135	0.2696
3/2/97 7:30	16	7	94.7	0.0009	0.0005	0.9164	0.2702
3/2/97 12:00	32	10	89.8	0.0017	0.0007	0.9166	0.2703
3/2/97 14:00	260	21	95.7	0.0150	0.0016	0.9173	0.2704
3/2/97 16:00	62	11	95.8	0.0036	0.0008	0.9181	0.2705

Table A-1. Continued

3/3/97 8:30	38	10	87.1	0.0020	0.0007	0.9200	0.2710
3/3/97 15:00	73	13	120.8	0.0053	0.0012	0.9210	0.2713
3/3/97 17:00	36	11	124.3	0.0027	0.0011	0.9214	0.2714
3/3/97 18:00	41	12	125	0.0031	0.0012	0.9215	0.2714
3/4/97 10:00	42	9	141.2	0.0036	0.0010	0.9237	0.2721
3/4/97 14:30	4	6	131	0.0003	0.0006	0.9241	0.2723
3/4/97 16:30	20	5	111.5	0.0013	0.0004	0.9241	0.2723
3/4/97 18:00	77	5	107.6	0.0050	0.0004	0.9243	0.2723
3/5/97 10:00	35	8	97.5	0.0021	0.0006	0.9267	0.2727
3/5/97 12:00	18	10	95.7	0.0010	0.0007	0.9268	0.2727
3/5/97 14:00	19	11	94	0.0011	0.0008	0.9269	0.2728
3/5/97 18:00	27	16	35.4	0.0006	0.0004	0.9271	0.2729
3/6/97 12:00	577	151	79.1	0.0276	0.0093	0.9376	0.2765
3/6/97 17:30	153	63	73.6	0.0068	0.0036	0.9415	0.2780
3/6/97 18:45	66	42	73.2	0.0029	0.0024	0.9418	0.2782
3/6/97 20:00	41	32	83.4	0.0021	0.0021	0.9419	0.2783
3/7/97 8:00	4	6	85.6	0.0002	0.0004	0.9425	0.2789
3/7/97 15:30	1	12	79.7	0.0000	0.0007	0.9425	0.2791
3/7/97 16:30	2	10	80.5	0.0001	0.0006	0.9425	0.2791
3/7/97 18:30	835	1215	97	0.0489	0.0915	0.9446	0.2830
3/8/97 9:00	1147	1291	91.6	0.0634	0.0918	0.9785	0.3383
3/8/97 14:00	320	275	92.9	0.0179	0.0198	0.9870	0.3499
3/8/97 15:00	142	185	92.8	0.0080	0.0133	0.9875	0.3506
3/8/97 17:30	36	52	94.4	0.0021	0.0038	0.9880	0.3515
3/9/97 10:00	15	23	96.3	0.0009	0.0017	0.9890	0.3534
3/9/97 13:30	4	23	104.1	0.0003	0.0019	0.9891	0.3537
3/9/97 14:30	0	9	103.1	0.0000	0.0007	0.9891	0.3537
3/9/97 17:00	10	24	103.3	0.0006	0.0019	0.9892	0.3539
3/10/97 12:30	0	6	8.68	0.0000	0.0000	0.9894	0.3547
						Final cumulative	

Table A-2. Soil Vapor

Envirionics Soil Vapor Sampling Results All concentrations in ppbv									
PRIMARY SAMPLES									
		V1		V2		V3		V4	
Date	Series #	PMCH	PTMCH	PMCH	PTMCH	PMCH	PTMCH	PMCH	PTMCH
6-Feb	000	0	0	0	0	0	0	0	0
7-Feb	001	0	0	0	0	0	0	0	0
11-Feb	002	0	0	0	0	0	0	0	0
18-Feb	005	210	9400	0	234	10400	0	50	0
20-Feb	006	3	11400	327	0	117	0	181	128
22-Feb	007	617.10327	7.69E+04	313.68521	3.44E+04	878.08728	483.06134	4834.9634	871.44061
24-Feb	008	161.90033	292.60208	168.96925	3308.6604	946.24933	2314.6023	826.96143	30.26926
25-Feb	009	1.57E+04	407.00546	2.24E+04	596.72699	6636.978	203.35934	260.70111	18.91865
26-Feb	010	0	0	126.52105	0	0	0	0	0
28-Feb	011	397.50632	103.81261	1.23E+04	2323.2083	384.23337	71.61581	1062.6742	203.90726
2-Mar	012	0	0	159.07036	15.1624	20.32532	0	0	0
4-Mar	013	0	0	3.18908	0	2.87963	0	0	4.28577
6-Mar	014	0	7.52019	1.29E+04	4230.165	1216.0211	361.95145	20.47086	7.37187
7-Mar	015	187.5565	102.28184	5	38.6	4.04392	27.38813	3.63174	27.44397
8-Mar	016	1155.1538	1014.2135	1893.0212	877.88287	795.16925	569.60333	511.526	441.28156
9-Mar	017	0	0	10.17523	10.30322	0	0	0	0
						Total Number of Analyses		128	
QA SAMPLES:									
Duplicates (D) and Replicate Analyses of Primary Samples (PR)									
3-Mar	V4014D							27.9	5.3
7-Mar	V2015PR			3.9	32				
28-Feb	V2011FD			8572.8	1603.8				
28-Feb	V2011D			12293	2267.7				
26-Feb	V3010D					4.1	0		
20-Feb	V1006D	3	11100						

Table A-2. Continued

Equipment Blanks (E) and Equipment Blank Duplicates (DE)				RPD, %				Difference, ppb			
				PMCH	PTMCH	PMCH	PTMCH				
9-Mar	AQ011E	31.3	11.9	Dirty syringe				31	33	7	2
8-Mar	AQ010E	39.7	58.5	Dirty syringe							
8-Mar	AQ009E	75.4	87.2	Dirty syringe							
8-Mar	AQ008E	42.6	85.7	Dirty syringe							
7-Mar	AQ007E	3.5	0								
7-Mar	AQ007DE	3.5	0								
27-Feb	AQ006DE	3.1	0								
27-Feb	AQ006E	1.9	0					0	2	19	56
	average	3	0					200	0	4	0
								0	3	0	300
Field Blanks (F)				Average		15	13	8	89		
6-Mar	AQ006F	0	4.2	Std Dev		22	17	8	143		
6-Mar	AQ005F	0	4.5	Stats computed using only values above detection limit of 4 ppb							
6-Mar	AQ004F	0	4.5								
6-Mar	AQ003F	0	4.6								
27-Feb	AQ002F	0	0								
	average	0	4								

Table A-3. Groundwater

Envirionics Groundwater Sampling Results All concentrations in ppbv													
PRIMARY SAMPLES		G1		G2		G3		G4		G5		G6	
Date	Series #	PMCH	PTMCH	PMCH	PTMCH	PMCH	PTMCH	PMCH	PTMCH	PMCH	PTMCH	PMCH	PTMCH
20-Feb	000	0	3.59E-03	0	9.58E-03	0	1.11E-02	0	1.55E-02	0	2.00E-02	0	2.75E-04
20-Feb	001	0	2.32E-02	0	1.16E-02	0	1.51E-02	0	1.24E-02	0	2.27E-02	0	1.85E-02
20-Feb	002	0	1.69E-02	0	2.87E-02	0	5.08E-03	0	3.95E-03	0	3.38E-03	0	2.46E-02
21-Feb	003	0	1.10E-02	1.69E-02	3.36E-02	0	2.97E-02	0	4.50E-02	0	4.37E-02	0	0
21-Feb	004	1.26E-03	0	0	3.83E-02	0	1.61E-02	0	2.44E-02	0	2.16E-02	0	6.03E-02
21-Feb	005	0	4.96E-02	1.62E-02	3.77E-02	0	3.20E-02	0	7.65E-02	0	1.62E-01	0	8.96E-02
27-Feb	006	0	5.85E-02	0	5.05E-02	0	6.17E-02	0	0	0	0	0	0
10-Mar	007	0	0	0	0	0	0	0	0	0	0	0	0
11-Mar	008	0	0	0	0	0	0	0	0	0	0	0	0
10-Mar	009	0	0	0	0	0	0	0	0	0	0	0	0
11-Mar	010	0	0	0	0	0	0	0	0	0	0	0	0
10-Mar	011	0	0	0	0	0	0	0	0	0	0	0	0
	012	0	0	0	0	0	0	0	0	0	0	0	0
10-Mar	013	0	0	0	0	0	0	0	0	0	0	0	0
	014	0	0	0	0	0	0	0	0	0	0	0	0
	015	0	0	0	0	0	0	0	0	0	0	0	0
	016												Total number of analyses: 192
	017												
													average, all: 6.37E-03
													average, non-zero: 3.06E-02
													std dev, all: 1.84E-02
													std dev, non-zero: 3.00E-02
QA SAMPLES													
	G1-009-D	0	0										
	G2-013-D	0	0										
	G3-005-D	0	8.00E-02										
	G3-015-D	0	0										
	QA-002-E	0	0										
	QA-002-F	0	0										
	QA-003-DF	0	0										
	QA-003-F	0	0										
	QA-003-E	0	0										
	QA-001-F	0	2.00E-02										
	QA-001-E	0	2.00E-02										
	QA-000-F	0	6.00E-03										
	QA-000-E	0	1.00E-02										

(This page is blank.)

NOTICE

PLEASE DO NOT REQUEST COPIES OF THIS REPORT FROM AL/EQ (ENVIRONICS DIRECTORATE). ADDITIONAL COPIES OF UNLIMITED DISTRIBUTION REPORTS MAY BE PURCHASED FROM:

NATIONAL TECHNICAL INFORMATION SERVICE
5285 Port Royal Road
Springfield, Virginia 22161

FEDERAL GOVERNMENT AGENCIES AND THEIR CONTRACTORS REGISTERED WITH DEFENSE TECHNICAL INFORMATION CENTER SHOULD DIRECT REQUESTS FOR COPIES OF THIS REPORT TO:

Defense Technical Information Center
Cameron Station
Alexandria, Virginia 22314

If your address has changed, if you wish to be removed from our mailing list, or if the addressee is no longer employed by your organization, please notify AL/EQPP, 139 Barnes Drive, Tyndall AFB, Florida 32403-5323, to help us maintain a current listing.

Copies of this report should not be returned unless required by security considerations, contractual obligations, or notices on a specific document.